Performance Modelling for Advanced Envelope Systems

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The Road not Taken

by Robert Frost - 1916

Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveller, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;

Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that, the passing there
Had worn them really about the same,

And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads to way,
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I-
I took the one less travelled by,
And that has made all the difference.

Abstract

The performance modelling of advanced envelope systems with respect to daylight illumination inside office spaces and quantifying their impact on the energy demand for electric lighting, based on real time-varying climatic conditions, is the focus of this thesis. The work involves daylight modelling using the Unix-based *Radiance* lighting simulation program, the adaptation of suitable calculation approaches, and the development of investigative models and custom-written data analysis programs.

A literature review is presented of daylight implementation strategies, artificial lighting components and controls, advanced envelope systems, and daylight modelling approaches. A formulation using the daylight coefficient approach and *Radiance* is selected and adapted for the purposes of this study. Conventional methods for daylight illuminance appraisal are revised before a new metric for evaluating the usefulness as well as the availability of daylight in an office space, rather than just at a point, is introduced.

A range of building envelope systems are reviewed, including tinted glazings, manual blinds, automatic blinds, and electrochromic glazings for the transparent area of the envelope, and building-integrated photovoltaics for the opaque area. In order to simulate the performance of these systems, models are developed which can take as input real time-varying meteorological data and then predict the internal illuminance distribution, the resulting energy consumption due to electric lighting, and the potential electric output in the case of building- integrated photovoltaics. The new daylight evaluation metric is used for assessing the performance of the different window systems based on hourly internal illuminance. Feasible scenarios coupling the operation of these systems with daylight-linked electric lighting controls are used to compute the lighting energy demand. Predicted hourly incident irradiation, computed PV cell temperature, and the electrical characteristics of a widely-used high-efficiency PV module are used for estimating the BIPV electric output.

The results are then compiled in a way which facilitates comparing and rating the performance of different envelope systems, facade orientations, and control strategies. The validity of applying the adopted approaches and the developed models in different climatic zones is also examined. The results obtained show that innovative envelope systems have the potential to significantly improve the luminous environment inside office buildings and effectively contribute to reducing the demand for electric lighting.

It is hoped that this study may prove to be useful to architects, building designers and developers, and that the proposed models and assessment methods can be helpful in realistically evaluating the performance of advanced envelope systems and quantifying the potential energy benefits of integrating such systems into buildings. It may also be of use to material developers since it can assist them in their research on improving their products and optimizing their performance.

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I declare that the content of the submission represents solely my own work.

Azza Nabil, September 2002

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Chapter 1

Introduction

"Rowe's Rule: the odds are five to six that the light at the end of the tunnel is the headlight of an oncoming train."

PAUL DICKSON 1939- (IN *WASHINGTONIAN*, NOVEMBER 1978)

In recent years, the impact of the world's energy consumption on the natural environment, with its unpredictable economical and ecological repercussions, has been an active debate worldwide [ETSU, 1999a]. Hence, in order to conserve energy, targets have been set to reduce the consumption of fossil fuels and to utilize energy more efficiently and cost-effectively. As a result of these targets, the fundamentals and the specifications for the design and construction of buildings are also changing [Sweitzer, 1991]. The focus of attention for many of these changes has been the building envelope. It is becoming a complicated, multi-functional component of the building as new technological developments are allowing conventional designs of facades and roofs to be replaced by significantly different concepts [Lee et al., 2000a]. In addition to protecting the occupants from the elements, the building envelope must meet the occupants' comfort requirements, the obligation to minimize energy use and resulting pollutants, and the demand to exploit the benefits of active and passive solar design [Hagemann, 1996].

Since lighting and cooling constitute the largest portion of electric energy demand in non-domestic buildings, it is worth considering the integration of innovative envelope elements, smart window devices, and advanced lighting technologies in a holistic building system [CADDET-EE, 2001]. This holistic concept presents a potential for a work environment of enhanced quality, as well as efficient management of energy use. With innovative daylighting systems, it is possible, in principle, to optimize internal illuminance levels, improve the daylight uniformity within a space, control direct sunlight, and/or reduce glare and discomfort for the occupants. These innovative systems include glazing of varying transmittance (such as electrochromics) and automated Venetian blinds. In addition, many studies indicate that the simultaneous control of artificial lighting systems (i.e., daylight-linking) can minimize electrical energy demand [Li et al., 2000].

In recent years also, the world has witnessed some interesting developments in the technology of embedded power generation, i.e., generating power at the point of use, particularly using renewable energy sources. This has been instigated by the environmental benefits of renewable energy compared to conventional methods of power generation, in addition to the incentive of avoiding, wherever possible, power transmission and distribution losses [Schoen, 1996]. The use of photovoltaic (PV) modules for generating electric energy from solar radiation has progressed and proved to be a successful application in the last three decades [Munro, 1999]. While implementing this technology in rural areas as off-grid installations was, to a large extent, aesthetically acceptable and economically justifiable, integration into the grid-connected urban environment has proved to be a lot more challenging. The high costs and scarcity of urban land have prompted the use of buildings for electricity generation, and aesthetic and economic considerations have called for innovative engineering and architectural integration of the PV modules into the building fabric. This way, the PV units replace and function as other parts of the building elements such as facade, glazing, or roof while also acting as power generators, thus increasing their cost effectiveness [ETSU, 1999b].

However, the successful implementation and integration into buildings and the prospects of wide-scale deployment of all the above technologies require careful modelling and design optimization. The performance of the various facade technologies, referred to as advanced envelope systems, is highly dependent on meteorological conditions and facade orientation, which existing assessment methods are not equipped to account for. These methods, therefore, are inadequate to quantify the performance of advanced envelope systems. Hence, the primary aim of the work described in this thesis has been to bring together advanced envelope, daylighting, and lighting designs in a viable building system, simulate their performance, and develop a method to accurately quantify their impact on the internal illumination and consumption of energy for electric lighting in office buildings. Also explored are some aspects of visual comfort. The technologies that were investigated in this study include automated blinds, electrochromic glazing, daylight-linked electric lighting controls, and building-integrated photovoltaics, applied on a generalized office module. The work entails the adaptation of appropriate calculation approaches and the development of investigative models and custom-written data analysis programs.

Chapter 2 contains a review of existing literature on daylighting strategies and lighting controls in non-domestic buildings, while daylight modelling approaches are reviewed in Chapter 3. In Chapter 4, daylight availability assessment methods are reviewed, and then a new metric is introduced as a tool for appraising the availability and usability of daylight in an office space based on realistic time-varying climatic conditions. Switchable window devices are reviewed in Chapter 5, and their performance with respect to internal illumination is modelled using the new metric. The associated operation of different daylight-linked artificial lighting controls and the resulting electric energy consumption are also investigated. Chapter 6 contains a comprehensive review of PVs and issues relating to their integration into building envelopes. Then, the performance of a building-integrated PV system is simulated using a proposed model and actual meteorological data, and its electric output is predicted for different facade orientations. In Chapter 7, the validity of applying the adopted approaches and the developed models for assessing the performance of advanced envelope systems in different climatic zones is studied. The grouping of the performance results as functions of device properties and implementation strategies facilitates the comparison between different systems. Chapter 8 contains a discussion of the results and the drawn conclusions and recommendations. The appendices include ancillary data and tabulated results.

Chapter

2

Daylight in Non-Domestic Buildings

"As half in shade and half in sun
This world along its path advances,
May that side the sun's upon
Be all that e'er meet thy glances!"

THOMAS MOORE 1779-1852 (*PEACE BE AROUND THEE*)

Daylight is considered the best source of light for good colour rendering. Its quality most closely matches human visual response [Li et al., 2001]. It is, however, a commodity that is generally taken for granted. Replacing it with artificial light was, before the twentieth century, considered very expensive. With the coming of cheap electricity, daylight has been neglected and most modern office buildings are designed to rely heavily on electric light [Boyle, 1996]. In fact, it is recognized that artificial lighting can be a major energy consumer in non-domestic buildings, and in recent years, greater acknowledgement has been given to the contribution that daylight can make to energy conservation [Steemers et al., 1993][Li et al., 2000]. To this end, interest is growing in more daylight-conscious architectural designs and the introduction of innovative daylighting systems and efficient lighting controls.

The exploitation of daylight, i.e., 'daylighting', has become internationally perceived as a valuable means of potentially improving the energy efficiency of non-domestic buildings and producing visually appealing interior spaces [Foster et al., 2001]. This term is primarily used in relation to commercial/ non-domestic buildings, in which the times of daylight availability and building occupation (i.e., normal working hours) mostly overlap, and therefore daylight could, in principle, displace a considerable part of the electricity consumption used for artificial lighting [Christoffersen et al., 1997].

While, traditionally, glazing was seen as a weak thermal link in a building's fabric, the last two decades have seen an increasing use of glass in the facade design of office buildings, mostly enabled through the development of multi-pane and gas-filled insulating windows. In fact, a pilot study by Foster et al. has provided an indication that many buildings are currently over-glazed, and that in spite of this, there is an increased use of electric lighting and, hence, energy use in buildings, compared to that predicted during the design stage of many buildings [Foster et al., 2001].

In addition, depending on the types of lamps installed, a greater or lesser fraction of the lighting load is converted to heat and thus affects the heating or cooling load of the building [Steemers et al., 1993]. It has been argued that in winter, the heat from artificial lights can usefully contribute to space heating energy thus reducing the heating requirements of the building. However, it has been also argued that better utilization of solar gains can in many cases substitute those heat gains, and that even if the solar gains cannot substitute all the internal heat gains emitted by lights, the increased auxiliary heating demand can be provided by 'low-grade' energy, i.e., oil or gas, as opposed to 'high-grade' electricity [Lerum, 1996]. In summer, on the other hand, the heat from artificial lights can cause overheating, especially in well-insulated buildings. In fact, many offices need to be cooled all year round [Boyle, 1996]. For these buildings, therefore, making better use of natural light can save on energy consumption for both artificial lighting and cooling loads[1].

Moreover, better use of natural light can possibly provide improvement in the quality of the working environment [ENEA, 1998]. Major studies have shown the quantifiable potential of daylighting to increase productivity in the workplace while also contributing to lowering energy bills [Bazilian et al., 2000].

2.1 Daylight Implementation Strategies

Appropriate and carefully designed fenestration and lighting controls can, in principle, be used to modulate daylight admittance and to reduce the use of electric lighting, while meeting the occupants' lighting quality and quantity requirements. Although there are few non-domestic buildings in which daylight can meet the entire lighting need, at the same time, there are few building types to which daylighting cannot make a significant contribution [CADDET-EE, 2001]. The degree to which daylighting can be used depends greatly on the geographic location and other conditions including latitude, building orientation, seasonal fluctuations in the number of available sunlight hours, the time of day, local meteorological conditions and outside obstructions. Various strategies for daylight implementation are discussed below, and some are sketched in the diagram of Figure 2-1.

2.1.1 Vertical Windows

Conventional vertical windows provide the most common and simple means of daylighting. They are considered most effective for lighting vertical surfaces that are directly facing and close to the glazed area. For most tasks, a window area of approximately 20% of the floor area is recommended to

1. Artificial lighting contributes to the internal heat gain of a building and must be accounted for when considering the capacity of an HVAC (heating, ventilation, and air-conditioning) system since it is believed that the heat load created by 2 kW of lighting in a building must be compensated by 1 kW of extra air-conditioning electrical energy [DETR, 1999][CADDET-EE, 1995].

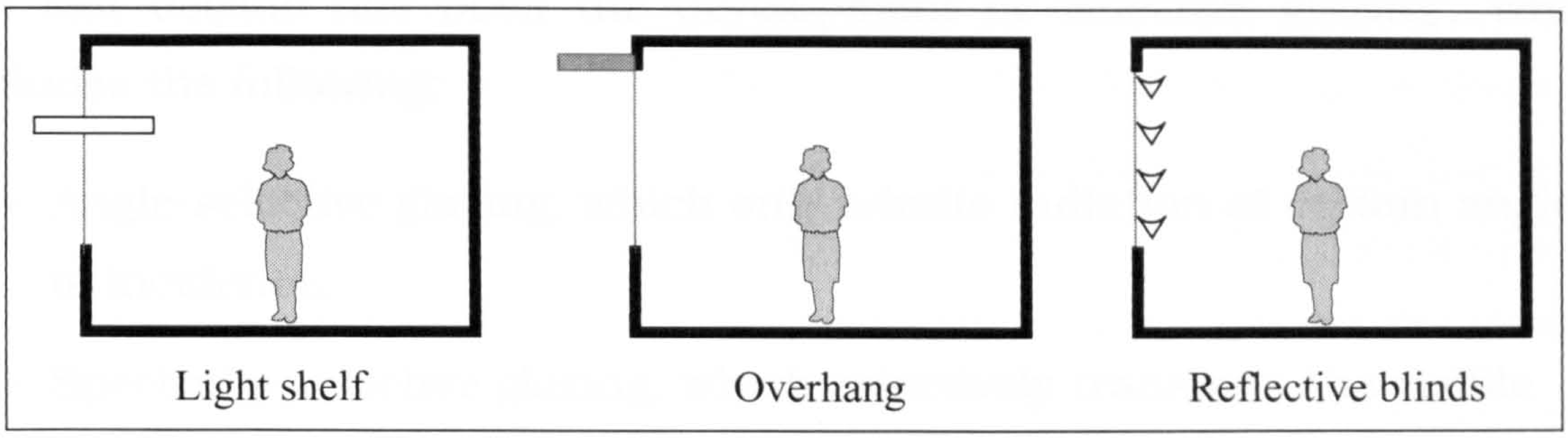

Figure 2-1 Examples of daylight implementation strategies

provide adequate daylighting to a depth of approximately 1.5 - 2.5 times the room height [CADDET-EE, 2001].

Daylighting using vertical openings is more dependent on room geometry than using roof openings, favouring extended building envelopes that bring most of the interior space within 8 - 10 metres of the facade [Selkowitz et al., 1998]. The recommended value of 'effective apertures[2]' is 0.2 - 0.3 for side-lit perimeter zones and 0.02 - 0.03 for top-lit buildings [LBNL, 1997].

2.1.2 Glazing Technology

Low emissivity coatings, coloured glazing, window films, and replacing air with a heavier gas between window panes are all examples of effective glazing methods aimed at reducing convection, conduction, and radiation transfer through windows. These measures can help reduce the effects that large areas of glazed facades have on other building systems, for example, excessive heating due to solar gain and heat loss due to lack of thermal insulation.

The development and widespread use of large area, low cost, multi-layer thin film coatings have been a most important innovation in glazing technology over the last 25 years [Selkowitz, 1999]. The primary objective of the initial coating development effort was the transparent, low-emissivity

2. The effective aperture is the product of visible transmittance and the window-to-wall ratio [LBNL, 1997].

(low-E) coating for glass and plastic. Another significant breakthrough in the last decade has been the development of 'selective glazing', which includes the following:

- Angle-selective glazing, which only admits radiation at certain angles of incidence.
- Spectrally-selective glazing, which selectively transmits the visible portion of the solar spectrum and rejects the near-infra-red portion, without altering the perceived colour of daylight[3].

Although these spectrally selective coatings are highly optimized to maximize the daylight/cooling load ratio, their optical properties are fixed and do not respond to changing sun and sky conditions. The next remarkable advances in coated glazings are expected to be what are referred to as 'smart', 'dynamic', or 'switchable' glazings, which respond dynamically to changing occupant and building needs by varying their light and heat transmission characteristics. After several years of laboratory development, these coatings are now beginning to be scaled up in prototype form for use in buildings [Selkowitz et al., 1998]. These switchable glazings are mainly either passively activated such as:

- Photochromic glazing, which darkens after reaching a threshold in light intensity (already used in sunglasses).
- Thermochromic glazing, which becomes opaque when heated by incident solar irradiation.

Or they are actively controlled such as:

- Electrochromic glazing, where a small electrical impulse through a transparent electrolyte layer changes the light transmission properties.

3. Approximately 50% of the energy in sunlight lies in the ultra-violet and near-infra-red wavelengths and can thus be rejected without reducing visible transmittance or altering the perceived colour of daylight [Selkowitz et al., 1998].

The primary advantage of dynamic glazing devices is the ability to integrate them with an automated control system to provide continuous control of the luminous environment (from both daylight and electric lighting). While each of the above devices should ultimately find a niche market, it is argued that the actively controllable electrochromic is likely to be the preferred choice, assuming the remaining durability and cost issues can be favourably resolved [Selkowitz, 1999]. Electrochromic glazing is discussed in more detail in Chapter 5.

2.1.3 Shading Devices

Of shading devices, external shading is generally considered to provide the most effective means of restricting heat from reaching an interior space. Overhangs can allow maximum winter sunlight penetration and reduce summer cooling loads. Internal shades, on the other hand, are regarded as more likely to protect occupants from immediate glare and direct sunlight.

Venetian Blinds

A Venetian blind system is a widely used, multi-functional device which can serve as glare protection, a barrier to unwanted solar gains, and a versatile/ flexible daylighting feature to redirect direct sunlight deeper into a space. The slats of Venetian blinds can be either flat or curved, and they are usually evenly spaced, with a distance between the slats less than the slat width to maintain a small overlap when fully shut/drawn. Venetian blinds can be used on all orientations and latitudes, but horizontal blinds are often used on a south-facing window (in the northern hemisphere), while vertical blinds are used on east- and west-facing windows [Christoffersen et al., 1997]. From measurements, approximately 20% of the incident light penetrates Venetian blinds when they are fully drawn (that is assuming that 100% of light penetrates the glazing without blinds) [Foster et al., 2001].

Blinds integrated into the window system appear to be an interesting development. Although these blinds use small amounts of energy, since they are usually automatically controlled, this is considered insignificant[4] compared to the energy savings derived. By adjusting the slat angle of thin reflective blinds embedded between layers of glazing, direct solar radiation can be prevented from penetrating the room beyond a given distance from the window, thus preventing unwelcome effects on thermal comfort. If there is no sunlight, the slats can be angled flat or raised/retracted altogether.

2.1.4 Atria

Atria are interior courts with glazed roofs, and they are among the most traditional forms of daylighting systems. They allow daylight penetration deep into central building areas, can join together a number of buildings, and can provide pleasant 'open' spaces for occupants.

2.1.5 Rooflights

The use of a horizontal rooflight (skylight) can provide approximately three times the amount of daylight as a vertical window of the same size [CADDET-EE, 2001]. Rooflights are considered to also offer a more uniform daylight distribution throughout the space as they can be placed closer to the centre. Suitable sunscreening should generally be provided, however, since rooflights allowing direct solar radiation can cause overheating. Prismatic or angular selective rooflights have the advantage over flat alternatives in that they can be designed to only allow the passage of lower level light, and thus, in principle, providing daylighting without overheating.

Clerestories

Vertical or near vertical rooflights, such as clerestories and roof monitors, are more often used than horizontal rooflights which often collect more light and heat in summer than in winter. Clerestories are typically placed above head height in high-ceiling areas, and because they are designed according to the zenith angle of the sun, they can regulate the amount of daylight

4. For example, in a study by Lee et al., the automated Venetian blinds motor required 1.8 W (12 V at 150 mA) [Lee et al., 1998b].

admitted into a space. They can obstruct the direct rays of the sun during the summer but admit and reflect sunlight into the space during winter.

2.1.6 Light Shelves

Light shelves are usually horizontal reflectors (external and/or internal) designed to modify daylight distribution by 'bouncing' light deep into a side-lit space. A light shelf reduces the admitted sunlight and skylight near the window and reflects light from its top (diffuse or specular reflective) surface onto the ceiling thus increasing reflection from ceilings and other internal surfaces and improving the uniformity of daylight distribution in the interior. As with all other daylighting features, to optimize the effect of light shelves or redirecting blinds, high reflective coatings (for example with 70 - 80% reflectivity) are needed on the ceilings (and walls) in order to promote maximum penetration of daylight deep into a space [LBNL, 1997].

Overall, a light shelf reduces the illuminance level on the working plane because it directly cuts off part of the view of the sky. The magnitude of the reduction at a given point depends on the distance from the light shelf and the position and depth of the light shelf. An interior light shelf at normal height[5] (~1.9 - 2.1 m. above floor level) would screen off most of the light from the sky on the working plane in the middle of the room, while an exterior light shelf would do this mostly in the area just inside the window [Christoffersen et al., 1997].

2.1.7 Light Pipes

Although deemed significantly more complex than most daylighting systems, light pipes (or light ducts) can transmit daylight, without much of the associated heat, to deep spaces inside a building. They are designed to provide light internally by collecting sunlight through heliostats,

5. The position of a light shelf is dictated by the configuration of the space (particularly ceiling height) and the eye level of a standing person to avoid reflected glare (the top of the shelf should not be visible to the occupants) and maintain view out [Christoffersen et al., 1997][LBNL, 1997].

concentrating the light through mirrors or lenses, and directing it to the interior of a building through highly reflective shafts.

2.1.8 Lighting Control Systems

Studies show that no daylighting system can result in energy savings unless it is integrated with a control system to adjust and reduce artificial lighting loads in response to daylight availability [CADDET-EE, 2001]. Ideally, separate sensors should monitor daylight levels at different points throughout a space, and a control system should automatically adjust artificial lighting accordingly in order to maintain a balanced light level across the space. Lighting control systems are reviewed in more detail in Section 2.3.

2.2 Artificial Lighting

Significant innovations in lighting and office technologies have been the impetus for vast changes in the commercial lighting industry in the past 20 years or so. Many high-efficiency components developed during that time are now becoming widely used. Luminaires and controls have been improved to produce energy-efficient lighting designed to address a whole new range of commercial lighting issues, most particularly the widespread usage of VDTs (visual display terminals) in the workplace [Johnson, 1995].

Lighting technologies are regarded as potentially one of the most applicable/feasible means of achieving energy-efficient design in buildings. In fact, energy efficiency in lighting in the UK is now a mandatory requirement through the Building Regulations, Part L [CADDET-EE, 2000a]. Electric lighting systems consist of three main components: lamps, luminaires, and ballasts.

2.2.1 Lamps

The overall efficiency of a lamp is governed by its luminous efficacy (the ratio of the light produced in lumens to the electrical energy consumed by the lamp in watts, lm/W) and its lumen maintenance (i.e., how well the lamp maintains the specified light output level throughout its life). Lamps are classified by their light producing mechanism and are either incandescent or discharge. Although incandescent lamps are still used for decorative and task lighting applications, discharge lamps tend to prevail within commercial buildings [CADDET-EE, 1995].

Incandescent Lamps

Incandescent lamps produce light by passing electricity through a tungsten filament, heating it, and causing it to glow. They have excellent colour rendering but short lives (the filament burns out after approximately 1000 hours) and very low luminous efficacies (typically in the range of ~8 - 15 lm/W) [CADDET-EE, 1995]. In fact, it is argued that an incandescent lamp could more accurately be described as a heat radiator since 90 - 95% of the energy consumed is radiated as heat, leaving only 5 -10% to be converted into light [Bartlett et al., 1991]. These lamps are, however, inexpensive, easy to handle, and can be operated directly on the mains electricity.

Tungsten-halogen lamps can offer a more energy-efficient incandescent option since the halogen gas suppresses filament evaporation by a chemical regeneration process. Hence, the life of the lamp is increased (~2000 - 5000 hours), a higher luminous efficacy is obtained (~16 - 25 lm/W), and lamp lumen depreciation due to bulb wall darkening (as a result of filament evaporation) is reduced [CADDET-EE, 1995][DETR, 1997b].

Discharge Lamps

Discharge lamps generally operate when an electric arc is passed through a gas, a metal vapour, or a mixture of gases and vapours, producing visible light. The striking of the arc is facilitated by a gas that is easily ionized and occurs when ballasts provide the proper voltage across the electrodes. Discharge lamps cannot normally be operated directly on the mains electricity but need control gear including a ballast and often an igniter to start the lamp.

Fluorescent lamps, which are a special type of discharge lamps, tend to dominate discharge lamps within commercial installations. In addition to an inert gas and a small amount of mercury, a fluorescent tube contains a phosphor coating on the inside. When the electric arc is struck between the lamp's electrodes, ultraviolet radiation is produced, which excites the phosphor coating to produce radiation at visible wavelengths (i.e., light). Through the discharge/fluorescent process, approximately 25% of the energy consumed by the lamp is transformed into light, and 75% is radiated as heat [Bartlett et al., 1991].

Fluorescent lamps have continually improved since they were first introduced and have become the most widely used energy-efficient artificial light source [CADDET-EE, 1995]. Some of the main developments which fluorescent lamps have undergone are changes in gas filling (krypton instead of argon) and the use of highly efficient phosphor coating. They have luminous efficacies in the range of 40 - 110 lm/W and can last up to ~18 times longer than incandescent lamps, depending on the type of lamp and its ballast [DETR, 1997b]. They have also achieved improved colour rendition, a larger selection of colour temperatures, and better lumen maintenance [CADDET-EE, 1995].

Small compact fluorescent lamps (CFL), which are smaller versions of the standard tube fluorescent, are capable of directly replacing incandescent lamps since they contain an integrated ballast necessary for operation directly on the mains electricity. In addition, unlike linear fluorescent lamps, CFLs are not space-demanding and permit greater possibilities in luminaire design[6].

Fluorescent lighting is considered the source of choice for dimming and switching systems because these lamps can be dimmed over a wide range

6. There have been debates regarding how much energy is used to produce a CFL, and whether this energy is so high that the advantage of the energy saved during the burning time will be reduced. However, studies show that only approximately 0.29% of the energy saved during the burning time (of 8000 hours) is equal to the energy used for the production, since a CFL with an integrated electronic ballast requires ~1.4 kWh to produce [Bartlett et al., 1991].

without changes in colour and can be turned on and off virtually instantaneously. In addition, with colour temperatures of 4100°K or above (i.e., cool colours), it can provide good colour temperature blending with daylight [LBNL, 1997]. Conversely, most high-intensity discharge (HID) lamps, such as metal halide, high pressure sodium, and mercury vapour, are not suitable for dimming applications because they suffer colour shifts as they dim, have a more limited dimming range, require approximately 1.5 - 6 minutes to run up to full output, and usually suffer a delayed restart when hot [LBNL, 1997][DETR, 1997b]. They are, however, particularly suited for floodlighting and illuminating large areas that need to be lit for long periods, such as warehouses or street lighting, due to their relatively long life and infrequent need for replacement.

2.2.2 Luminaires

A luminaire comprises housing for one or more lamps, a reflector to provide the desired distribution of light, and a shielding component to shield the lamps from the occupants' eyes at normal viewing angles and reduce visual discomfort. In general, luminaires serve to distribute, diffuse, and direct light, control glare, and provide decorative aspects. Through appropriate material selection and precise shaping, a luminaire can direct the light to where it is required in order to optimize the usage of light emitted by the lamp and thereby reduce the overall lighting load. Direct/indirect lighting is regarded as generally more efficient at providing task illuminance than an indirect system [LBNL, 1997].

Luminaire efficiency is denoted by the 'light output ratio' (LOR) quoted by the manufacturer. This is the ratio of the luminaire's light output relative to the light output of the bare lamp (or lamps) in the luminaire. For most situations, a luminaire with an LOR of 0.5 or greater is recommended, but to some extent, this will depend on the light output distribution required [DETR, 1999].

2.2.3 Ballasts

All discharge lamps require ballasts, which through means of inductance, capacitance, and/or resistance, create the right conditions to start the discharge (ignition) and to regulate the voltage and current for proper operation. A ballast is mainly electromagnetic or electronic.

Electromagnetic Ballasts

Electromagnetic ballasts make use of inductors and capacitors to achieve the required current control. Despite their low initial cost, they consume approximately 10 - 20% of the total input energy [CADDET-EE, 1995].

Electronic Ballasts

Electronic ballasts use solid-state technology. Although initially more expensive than electromagnetic ones, they offer considerable cost savings in the long term and excellent overall performance characteristics. They convert the lamp operating frequency from 50 or 60 Hz (mains frequency) to 20 - 60 kHz, which results in a more efficient conversion of electricity to light [CADDET-EE, 1995]. They may be 'rapid-start' for instantaneous light or 'soft-start', in which there is a moment's delay.

Electronic ballasts have significantly lower internal losses than electromagnetic ballasts, and they have eliminated many of the non-desirable effects associated with electromagnetic ones, such as the buzzing sound, perceived lamp flicker, and flashing when starting [CADDET-EE, 1995]. Although all ballasts consume electricity, electronic ballasts consume up to 30% less circuit power than their electromagnetic equivalents for a given light output (due to less power loss) [DETR, 1997b]. In addition, electronic ballasts enable the artificial lighting to be dimmed effectively, prolong the service life of the lamp (~30 - 50% longer life), and result in a smaller decrease in light output over the lamp life [Ottosson, 1991][Bartlett et al., 1991].

2.3 Lighting Controls

In the UK, domestic lighting is said to account for approximately 2% of the delivered energy use while in offices, lighting can account for up to 30% of the delivered energy use and up to 50% of all electricity consumption[7] [Boyle, 1996][CADDET-EE, 2001]. The capital cost for an electric lighting installation, however, accounts for only approximately 3 - 5% of the total cost of an office building [DETR, 1999].

In general, energy-efficient lighting can be achieved through minimizing two variables: hours of use and installed power [CADDET-EE, 1995]. Linking daylighting strategies and lighting controls can minimize the hours of use by providing an adequate amount of artificial lighting only when necessary. Choice of artificial lighting components and their maintenance can minimize the installed power by optimizing the conversion of electric energy to light.

A good daylighting design may fail to achieve the expected energy savings performance because of failures in the lighting control systems. These include product design (sensor and electronics), architectural design (placement), installation, calibration, and operational problems [Selkowitz et al., 1998]. Ironically, it has been reported that a disabled lighting control system usually ends in a state that causes maximum energy consumption since a disconnected sensor results in the lighting going to full power. This is because for safety considerations, today's lighting control systems are designed in such a way that the lights are set to be on full power in case of a failure in the control system [Rubinstein et al., 1997].

2.3.1 Potential Benefits of Lighting Controls

In the UK, commercial lighting (which includes office buildings, hotels, recreational establishments, restaurants, services and wholesale/retail

7. Some studies carried out in the UK for naturally ventilated cellular offices demonstrate that approximately 50% of the cost of the energy consumed can be attributed to artificial lighting [Rossi et al., 1995].

outlets) accounts for ~63% of the total lighting load, and in the US, it accounts for ~57% [CADDET-EE, 1995]. Most often, a significant amount of energy is wasted through inefficient or malfunctioning lighting systems and/or inefficient operation by the building's occupants. Therefore, lighting controls in commercial/non-domestic buildings in particular have the potential to save significant amounts[8] of otherwise wasted lighting.

Energy and Cost Savings

Major savings in both energy and running costs can be achieved by using controls to operate electric lighting only when it is required, i.e., when daylight is insufficient and the workplace is occupied. Savings can also be achieved by adjusting the light output of a luminaire to provide the required illuminance throughout the maintenance cycle of the installation (known as 'design-maintained illuminance') [DETR, 1997a]. It should be noted, however, that for lighting controls to capture significant energy savings, they must be properly designed, specified[9], installed, commissioned and maintained [Rubinstein et al., 1997].

User Satisfaction

The importance of providing users with accessible and individually adjustable controls, and the consequences of doing so, is the subject of ongoing discussion and debate. It has been argued that if any automatic lighting control system is to meet user approval, it must allow for user adjustment of some of the control parameters. Studies conducted by the Building Research Establishment (BRE) in the UK have shown that higher user satisfaction and high energy efficiency were associated with high levels of local control, and that performance may be enhanced if people have

8. In offices, it has been reported that the synthesis of a properly daylit space and a well controlled artificial lighting system can produce energy savings in the range of 30 - 50% [CADDET-EE, 1995].

9. Specification can be difficult because the components that comprise the final system are not usually produced by the same manufacturer, and inter-operability of components from different manufacturers is reported to have always been problematic in the buildings industry [Rubinstein et al., 1997].

adjustable task lighting [Vine et al., 1998][CADDET-EE, 2000a]. Conversely, where users had little or no control over the lights in their workplace, or low awareness of the proper use of the controls, low satisfaction and energy wastage were common [Vine et al., 1998]. That said, the adjustments left for the user must be few enough in number to be easy to use and not add unnecessarily to the system's expense.

In December 1997, during a round-table on lighting controls[10], sponsored by the Lighting Research Centre (LRC) and Lawrence Berkeley National Laboratories (LBNL) in the U.S., it was suggested that the 'right' lighting control system allowed the user to control the luminous environment but did not require it, and that personal control had to be an option, even if it were not used [LRC, 1998]. In other words, it is important to provide the occupants with override capabilities and the ability to reset control levels, but much of the hour-to-hour adjustment is best left to a properly designed and calibrated automated system.

Flexibility of Space Use and Organization

Modern workspaces are often designed to be flexible to allow for space re-organization and revised occupancy patterns. When new tasks are introduced requiring different lighting, or when changes to the workspace result in walls or partitions being removed, major expense can be avoided if lighting circuits and light output can be altered without disturbing the fixed wiring. This is possible with dimmer-controlled lighting and luminaires that can be individually controlled remotely rather than from wall-mounted switches [DETR, 1997a].

2.3.2 Types of Lighting Control Systems

As mentioned earlier, daylighting techniques produce energy savings only if associated responsive and effective artificial lighting controls are in

10. Participants, including end-users, manufacturers, industry groups, government organizations, and researchers, were asked a few questions about what they thought was an ideal lighting system for offices [LRC, 1998].

operation. That said, the amount of energy saved depends entirely on the type of control strategy and techniques. According to BRE publications, case studies have shown that in a conventionally daylit commercial building, the choice of lighting control can make 30 - 40% difference to the resultant lighting use [Littlefair, 1998]. Most often, control systems are combined to achieve a maximum amount of savings and regulate the light as accurately as possible.

Lighting control systems can generally be divided into two main categories: manual and automatic. The selection of an appropriate control system should correspond with the amount of daylight available and the occupancy patterns of the space.

2.3.2.1 Manual Control

In areas with large occupancy, varied lighting levels are usually desired. Localized switching can be implemented in a variety of ways including pull cords on each lamp, hand-held infra-red remote controls, and control through an internal telephone network. The enabling of lights to be controlled within a small designated area can produce significant energy savings in comparison to a system that controls the entire space or building with one switch [CADDET-EE, 1995].

It should be noted, however, that through experiments carried out by the BRE to determine lighting use in manually-switched installations, it was concluded that although people were good at deciding whether the lights needed to be switched on, they were not as good at switching them off [Littlefair, 1998].

2.3.2.2 Automatic Control

Automatic control systems are generally divided into three types: time switching, occupancy linking, and daylight linking.

Time Switching

Time switching can be a highly effective yet simple means of lighting control. It can be implemented by programming lights to either switch off after being on for a specified amount of time (particularly effective for rest rooms and closets where unused lights are frequently left on) or to provide lighting through designated periods (for example, switching lights off during lunch breaks and at the end of the working day). The extinguished lighting can then be re-activated manually, or the system can be programmed to activate it at a given time.

Occupancy Linking

Occupancy linking control systems, where infra-red, acoustic, ultrasound, or microwave sensors are used to detect movement or noise, are considered most effective for spaces that are used intermittently [CADDET-EE, 1995]. They can also be useful in rooms where people are likely to have their hands full on entering (for example, store rooms). Upon detecting occupancy, the system switches the lights on, and after a time-delay, off again. The time delay allows people to leave the space safely and avoids lights being constantly switched on and off (when occupants are still or quiet). Another option is that the occupant switches the lights on manually when required, and the system switches them off when no occupancy is detected, i.e., 'absence sensing'.

Daylight Linking

Within a daylight-linked control system, photoelectric sensors measure the amount of daylight present and adjust the amount of artificial lighting accordingly. The photoelectric sensors can be placed centrally to control several luminaires or mounted on each luminaire for individual control, which is considered more desirable (since it would allow light to be regulated according to the illuminance requirements in each part/zone of the space) [CADDET-EE, 1995]. Daylight-linked control systems operate in the form of either 'on/off switching' or 'continuous dimming'.

A variant of the on/off control is the 'differential switching' photoelectric control, which reduces rapid switching of lights on and off when daylight levels are temporarily fluctuating around the switching illuminance (for example, due to moving clouds). This is because, unlike the standard photoelectric switch, the differential control has two switching illuminances: one at which the lights are switched off, and another lower illuminance at which the lights are switched on. Another advantage claimed for the differential switching control is that it can make switching off less obtrusive to the occupants as it is performed when daylight represents a higher proportion of the illuminance to which the eye is adapted [Littlefair, 1998].

Another way to reduce the frequency of light switching operations is to introduce a time delay into the process. It can be 'a switching-linked time delay' where switching off cannot occur until at least *n* minutes (a pre-set delay) after the last switch on, or 'a daylight-linked time delay' where switching off cannot occur until the daylight illuminance has exceeded the target value for *n* minutes. It is believed that of the two delay strategies, a daylight-linked time delay gives significantly less switching, and hence a shorter time delay can be used [Littlefair, 1998]. A typical value of 30 seconds was reported in the literature [LBNL, 1997][Lee et al., 1999].

A higher initial cost notwithstanding, photoelectric continuous dimming can provide greater energy savings than switching, which may also become obtrusive and bothersome with rapidly changing daylight conditions. Although tolerance for fluctuation in electric lighting levels varies (and is quite subjective), changes through dimming are considered to be less conspicuous[11]. Continuous dimming systems will be discussed in more detail in the following section.

11. People experience lighting fluctuation all the time in the natural environment, but it has been reported that they tend to find changes in the artificial lighting environment more disturbing [LBNL, 1997].

Dual-level or multi-level switching, which reduces light levels by turning off individual lamps in 2-, 3-, or 4-lamp fixtures, can also be activated by daylight sensors at less cost than dimming and is generally believed to receive better acceptance from the occupants than simple on-off controls [LBNL, 1997].

Studies comparing energy savings from different control systems have shown that savings greatly depended on the occupancy patterns. For example, in offices whose occupants tended to stay at their desks all day, dimming strategies saved more energy. Conversely, occupants who came in and out of their offices frequently (for time periods longer than the sensor time delay) obtained the greatest energy savings from occupancy sensors [Jennings et al., 2000]. It should be added that daylight sensing can be combined with occupancy sensing in one system so that even if daylight is inadequate, the electric lights will not be switched on unless the room is occupied.

2.3.3 Daylight Responsive Dimming Systems

As noted earlier, more daylight in interior spaces can lead to savings on electric energy only if the artificial lighting is switched or dimmed according to the amount of daylight penetrating the space and the required illuminance level. Daylight responsive dimming systems integrate daylight and electric light in a way which is aimed at maintaining the resulting workplane illuminance equal to or above a certain target illuminance level with minimum use of electric lighting.

Hence, a daylight responsive dimming system automatically controls the light output of the dimmable luminaires in response to daylight in order to maintain a previously specified light level. Each luminaire is equipped with an electronic dimming ballast, which is capable of dimming the lamp output smoothly and uniformly. Accordingly, these automatic lighting control systems are a viable option for reducing the electric lighting energy consumption in spaces where daylight can provide a considerable part of the illumination requirements[12]. In addition, through a study conducted by Love, it was found that reduced ballast voltages in automatic dimming systems resulted in significantly increased lamp life (even doubling in one case), which could significantly offset the relatively high initial cost of these systems [Love, 1995].

The basic components of the system are photosensors and luminaires, Figure 2-2. Daylight distribution and the ratio of illuminances between the

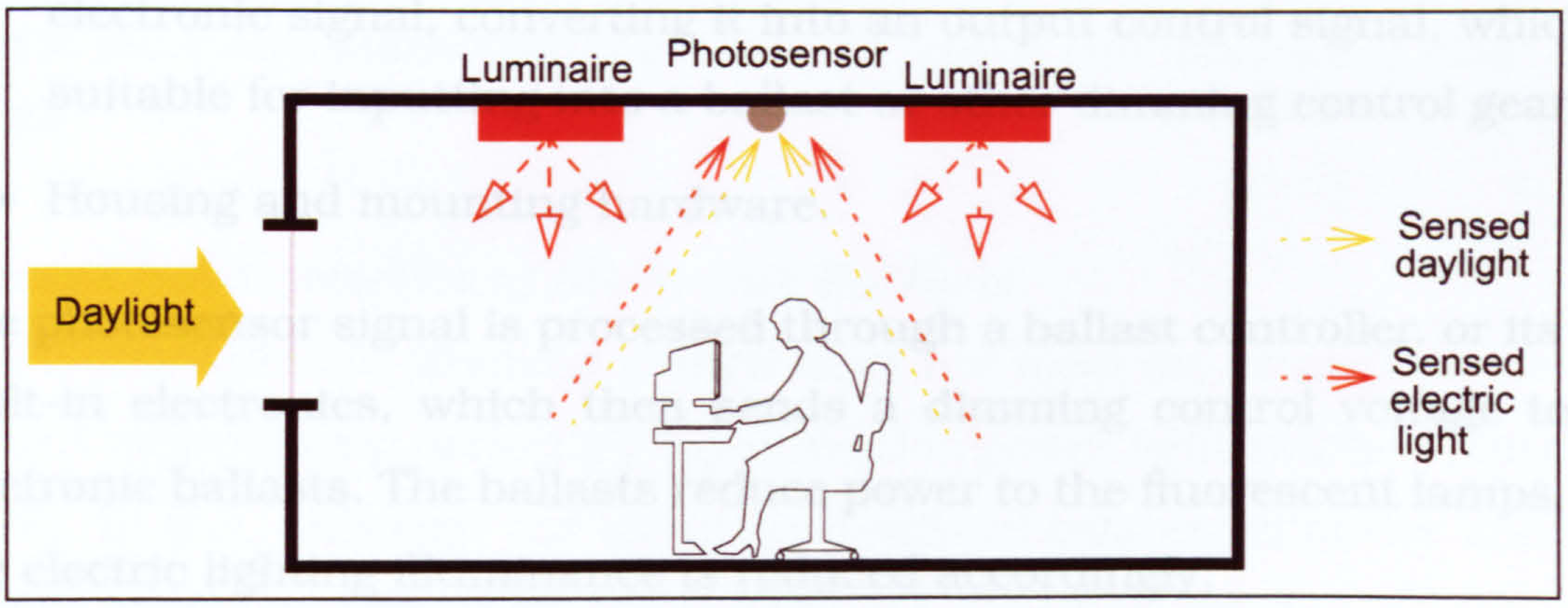

Figure 2-2 Basic components of a daylight responsive lighting system [re-drawn from LRC et al., 2000]

workplane and the ceiling (as discussed below) affect photosensor performance and so are critical for determining the proper photosensor location. Hence, the characteristics of the controlled space (i.e., physical dimensions, surface properties, occupancy patterns, etc.) should be considered when selecting an appropriate control algorithm. The orientation of the photosensor, as well as the dimming level, should be determined according to the control algorithm used.

12. For example, it has been reported that for day-time occupied commercial buildings, total electricity and peak demand savings of 20 - 40% in lighting and its associated cooling energy can be achieved with the proper use of dimmable daylighting controls throughout the U.S. [Lee et al., 1999].

2.3.3.1 Photosensors

A photosensor is typically a small unobtrusive device which contains the following elements:

- Input optics that collect a sample of the light in a space (by 'looking' at a wide area of the floor and work surfaces).
- A light sensitive component, i.e., photocell, that converts the optical signal to an electronic one.
- An electronic circuit, i.e., controller, to amplify and process the electronic signal, converting it into an output control signal, which is suitable for inputting into a ballast or other dimming control gear.
- Housing and mounting hardware.

The photosensor signal is processed through a ballast controller, or its own built-in electronics, which then sends a dimming control voltage to the electronic ballasts. The ballasts reduce power to the fluorescent lamps, and the electric lighting illuminance is reduced accordingly.

For precise control of the workplane illuminance, the ideal location for the photosensor is on the workplane. However, the workplane is not a practical location because the photosensor would likely be disturbed, covered up, or shaded by objects and activities in the room. In addition, a workplane-located sensor would be difficult to electrically connect to the rest of the control circuitry. Therefore, for practical reasons, photosensors are located on the ceiling to minimize this interference.

Controlling workplane illuminance with a sensor located on the ceiling, however, makes photosensor control complicated. For example, a ceiling-mounted photosensor does not directly measure the illuminance at the workplane. The best that can be achieved is a photosensor signal that is approximately proportional to the workplane illuminance since this signal is the only information available to the controller about the state of the lighting environment. Some controllers support inputs from more than one photosensor, which allows daylight to be sampled at more than one location.

Moreover, because of the photosensor's position on the ceiling, it receives light from the workplane below, as well as from other room surfaces. Hence, the photosensor often needs to be shielded from stray light from the window, electric lights, and ground-reflected light in order to better track interior illuminance levels. Some photosensors are wholly contained in one enclosure while others have separate sensor and electronic units, in which case, the electronic unit, i.e., the controller, can be mounted at a location that is more accessible than the ceiling for easier commissioning [LRC et al., 2000].

Power Characteristics of Electronic Ballasts

A real photoelectric dimming control does not have the ideal characteristic of light output being perfectly proportional to power consumption [Littlefair, 1998]. In fact, although the variation trends of consumed power and light output from the controlled luminaires are generally similar, as the rated percent values decrease, the difference between them increases, as shown in Figure 2-3 [Choi et al., 2000]. In high frequency control of fluorescent

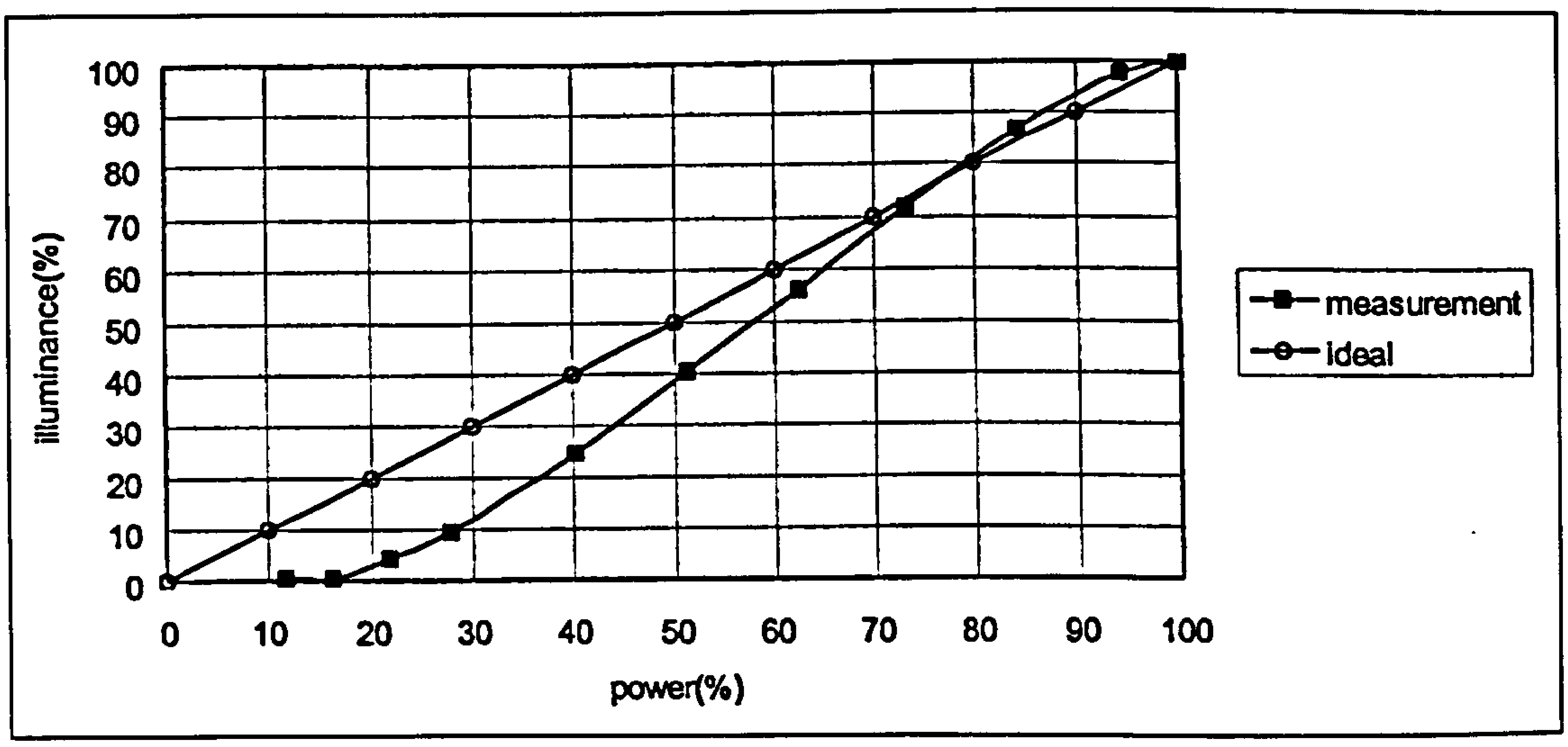

Figure 2-3 Relation between consumed power and resulting illuminance using an electronic dimming ballast (ideal and real behaviour) [Choi et al., 2000]

lighting, typical reported values for the electronic circuitry are 12.5% of full light output corresponding to 33% of full power consumption for the longer-established form of dimmers, with lower values for more recent and sophisticated types [Littlefair, 1998]. Power consumption can be further reduced if the circuit is switched off by the occupants, an occupancy sensor, or a time switch (rather than being maintained at the minimum dimming level), particularly in very well daylit spaces where illuminances often exceed the target value.

2.3.4 Daylight Control Algorithms

As previously cited, the role of the controller is to transform the photosensor signal into a command signal for the dimming ballast. The specific functional form of this transformation is termed 'the control algorithm' or 'the dimming response function'. It should be noted that if the algorithm used by the controller does not compensate for the fact that the control photosensor is usually positioned on the ceiling rather than at the workplane, then the daylighting control objective will not be attained.

According to the control algorithm, the dimming ballast actively controls the electric light level by altering the amount of power flowing to the lamps. 'Feedback' is said to be present when a signal path links the output (the light from the luminaire) to the input (the optics of the photosensor).

In general, there are three basic control algorithms that are used to convert the photosensor signal to the required dimming voltage: closed-loop integral reset, open-loop proportional, and closed-loop proportional. Each algorithm expresses a different relationship between the photosensor signal and the output of the electric lights as detailed below.

Closed-Loop Integral Reset System

A closed-loop integral reset system adjusts the control voltage, and hence the electric light output from the luminaires, to keep the photosensor signal at a constant level. This system has one adjustable parameter, the set (target) point. The optical signal on the photosensor is maintained constant as long as the required level of the electric light is within the dimming range of the ballast, which typically corresponds to a maximum of 100% electric light output down to a minimum dimming level of 5 - 20% of the maximum light output [LRC et al., 2000]. If the electric light level cannot be increased enough to maintain a constant photosensor signal, the control voltage remains at the maximum level, and the photosensor signal falls below the set-point. Conversely, if the electric light level cannot be dimmed enough to maintain a constant photosensor signal (i.e., more than enough daylight is present to provide the constant photosensor signal), then the control voltage stays at a minimum level, and the photosensor signal increases beyond the set-point, Figure 2-4.

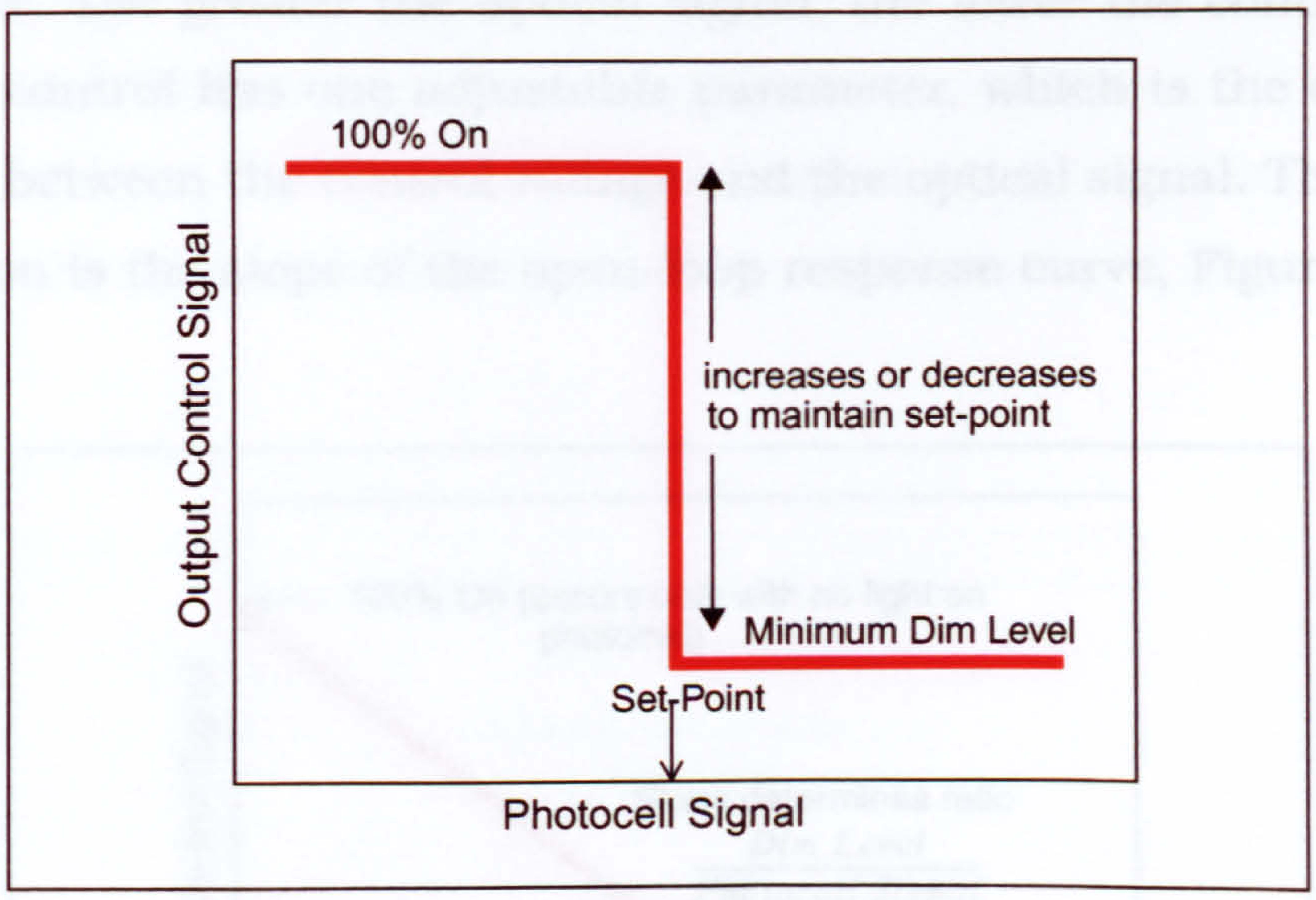

Figure 2-4 Response function of closed-loop integral reset system under open-loop conditions (i.e., when no feedback is present) [re-drawn from LRC et al., 2000]

Because the photosensor is typically on the ceiling not the workplane, and because the light distribution within a room differs when daylight is present compared to electric light alone, keeping a constant ceiling illuminance will usually result in the workplane illuminance falling much below the target value as daylight enters the room, a phenomenon called 'illuminance sag'. For this reason, the use of a high gain control algorithm (i.e., integral reset control) is not recommended in common building applications in which daylight enters the space through a side window and the electric lighting is mainly direct. It should be noted, however, that while this algorithm is not favoured for daylighting controls, it is considered the appropriate approach for a lumen maintenance control strategy [Rubinstein et al., 1988].

Open-Loop Proportional Control System

In an open-loop system, the photosensor does not respond to or 'see' the electric light that it controls. It is positioned such that it is exposed to daylight alone, i.e., mounted on the outside of the building or, more commonly, inside but facing the window. No feedback control is used for an open-loop system. The system adjusts the control voltage (and consequently the light output) as a linear function of the incident light on the photosensor. The greater the optical signal, the lower the control voltage. Open-loop control has one adjustable parameter, which is the constant of proportion between the control voltage and the optical signal. The constant of proportion is the slope of the open-loop response curve, Figure 2-5.

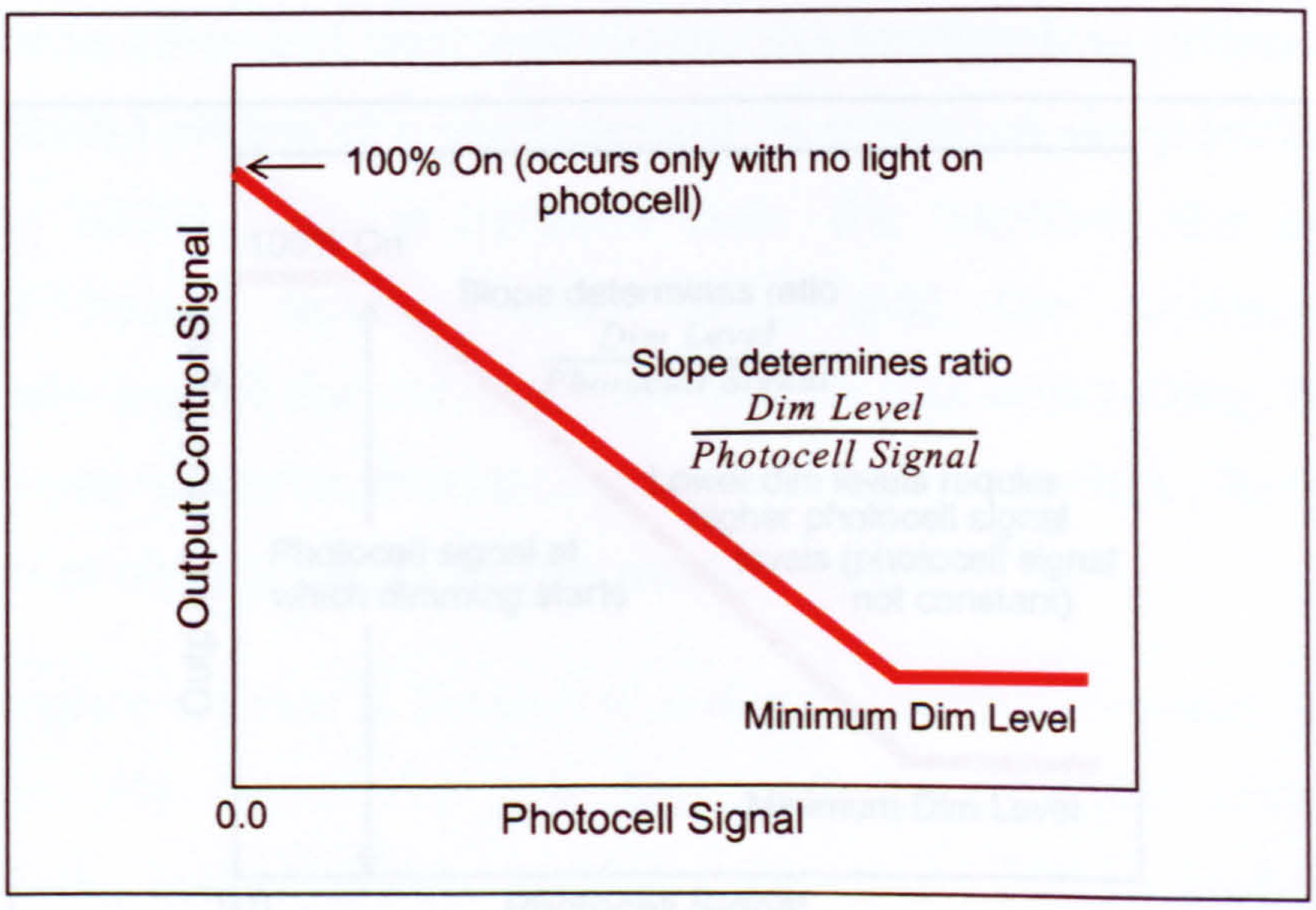

Figure 2-5 Response function of open-loop proportional control system [re-drawn from LRC et al., 2000]

This system results in wasted electric light capacity since it will never be able to deliver the maximum electric lighting level (except at night-time) [LRC et al., 2000]. This is because according to the open-loop response curve (Figure 2-5), whenever the optical signal on the photosensor is greater than zero, the control signal is less than maximum, and so the electric light is dimmed whenever any daylight is available/detected. In addition, open loop systems cannot compensate for electric light losses due to lamp aging and dirt depreciation (i.e., lumen maintenance).

Closed-Loop Proportional Control System

In a closed-loop system, the photosensor is positioned inside the building, usually on the ceiling facing the floor. Thus, it is exposed to both daylight and the electric light in the room, but unlike the integral reset system, the photosensor signal is not kept constant. Rather, the controller adjusts the electric light output so that the dimming level is a linear function of the difference between the photosensor signal and the maximum electric lighting night-time photosensor signal (i.e., reference level), Figure 2-6 [LRC et al., 2000].

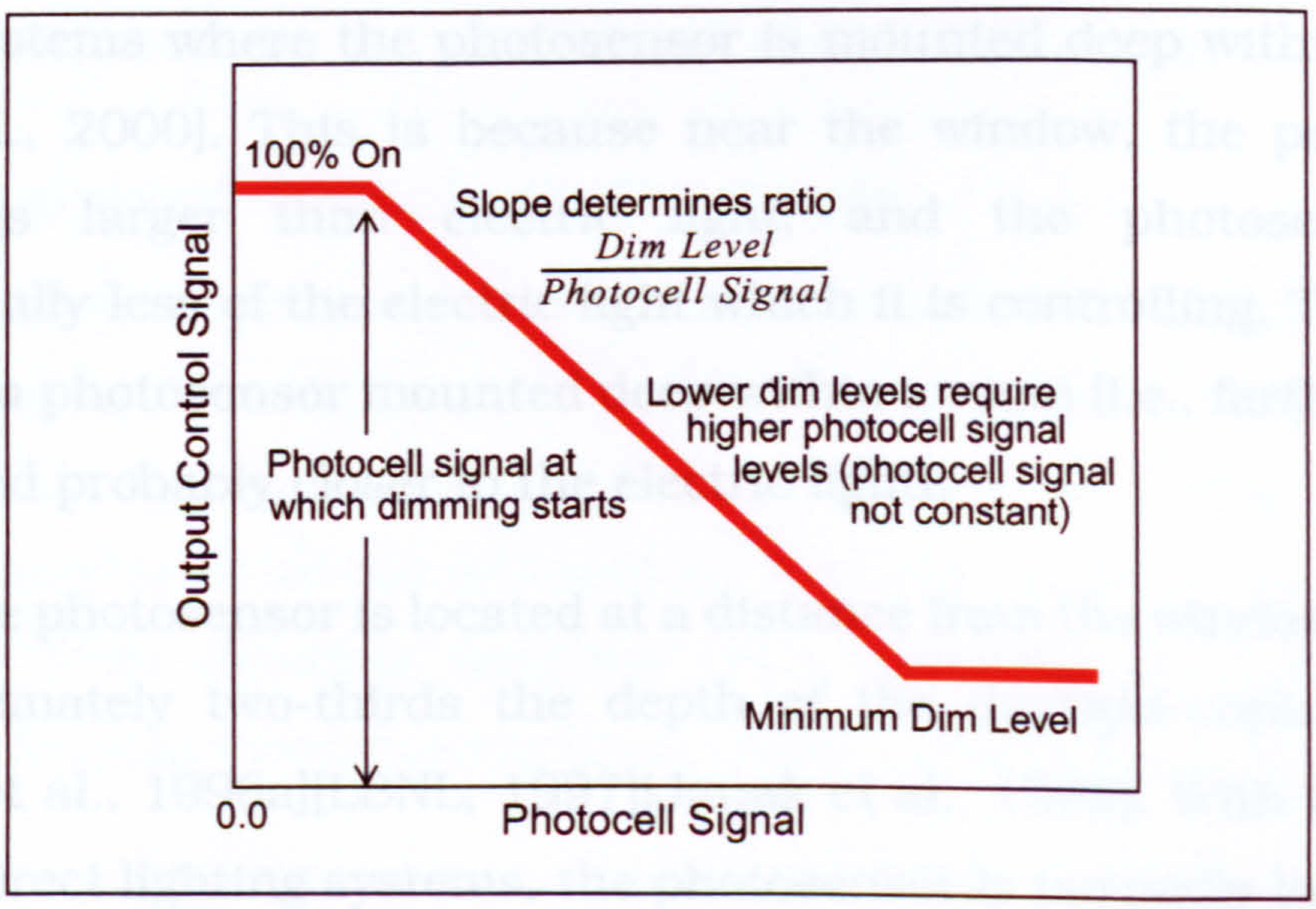

Figure 2-6 Response function of closed-loop proportional control system under open-loop conditions (i.e., when no feedback is present) [re-drawn from LRC et al., 2000]

As such, the closed-loop proportional control algorithm is identical to the open-loop control algorithm but with the addition of an offset to the dimming curve. The offset prevents dimming until the optical signal on the photosensor reaches the required set-point level. Hence, the closed-loop proportional control algorithm has two adjustable parameters: the constant of proportion between the control voltage and the input optical signal (the slope of the open-loop responsive curve), and the offset (the input optical signal where dimming starts). Therefore, this algorithm is regarded as the one which offers the most adjustments to the user and accommodates to some extent the different response characteristics of the photosensor to daylight versus electric light [Lee et al., 1999].

In this algorithm, the sensing of the electric light sends a feedback loop. Closed-loop systems use negative feedback to respond to changing luminous conditions, whereby an increase in an input signal causes a decrease in the output signal, i.e., an increase in the amount of light in the room causes a decrease in the electric light intensity, and vice versa. The amount of feedback, however, can vary for different systems and different locations of the system components. For example, in systems where the photosensor is mounted near a window, the feedback is proportionally less than in systems where the photosensor is mounted deep within the room [LRC et al., 2000]. This is because near the window, the proportion of daylight is larger than electric light, and the photosensor 'sees' proportionally less of the electric light which it is controlling. The opposite is true for a photosensor mounted deep within a room (i.e., farther from the window and probably closer to the electric light).

Usually the photosensor is located at a distance from the window equivalent to approximately two-thirds the depth of the daylight-controlled space [Sullivan et al., 1996a][LBNL, 1997][Janak et al., 1999]. With indirect and direct/indirect lighting systems, the photosensor is normally located in the plane of the luminaires aimed downwards. For direct lighting systems, on the other hand, it is recommended to have the photosensor recessed in the ceiling so that it would not directly see the electric lights [LBNL, 1997].

At the commissioning stage, the electric lighting offset (i.e., photosensor response to the electric lighting output at full power) is set at night. The slope of the linear function, which determines the photosensor signal to ballast dimming control voltage, is set once during the day with the electric lights on under typical daylight conditions.

Using scale models, data measurements by Rubinstein et al. to compare the above-mentioned three control algorithms showed that the best performance for daylight-linked lighting systems was obtained with closed-loop proportional control using a photosensor with a large field of view but shielded from direct light from the window [Rubinstein et al., 1988]. This system was shown in these experiments to provide the required design light level at selected workplane locations throughout the day regardless of room geometry or Venetian blind position.

As reviewed in this chapter, it can be said that in today's world, there is no shortage of devices and controls which, when properly designed and implemented, can have the potential to optimize the use of natural light in buildings and minimize consumption of electric lighting energy.

2.4 Advanced Envelope Systems

An advanced envelope is one in which a new facade technology is applied to optimize one or more aspects of a building's performance, such as thermal insulation, daylighting, solar control, ventilation, or energy generation. Typical examples of advanced envelope systems range in their degree of complexity from dynamic windows with advanced glazings to multi-functional facades incorporating photovoltaics [Baker et al., 2000].

In addition, with the current trend towards energy-efficient design solutions, these developments in building envelope technologies with variable physical properties (i.e., dynamic) have created new opportunities to achieve significant savings in building energy, peak demand, and cost, with potentially enhanced occupant satisfaction. Some of these technologies have proven successful for specific or general building applications, while others are still under development and testing to determine their limitations and potential benefits.

Dynamic building envelope technologies include the following:

- Dispersed liquid crystal glazings (clear to translucent state with applied voltage).
- Fluidized glazings and frames (act as radiators to provide variable thermal conductance).
- Controlled natural ventilation windows.
- Motorized shades and screens.
- Automatically controlled Venetian blinds (modulating the tilt angle of the slats).
- Electrochromic glazings (clear to coloured state with applied voltage[13]).
- Photovoltaic building facades.

Coupled with electric lighting control systems, dynamic envelope and daylighting systems can be actively controlled on a small time-step (for example, 10 minutes or less) in order to reduce the largest end-use contributors to commercial building electricity consumption: lighting and cooling [Lee et al., 1994]. This can be particularly valid and appreciated in climates with moderate daylight availability and for building types that are cooling-load dominated (such as offices).

It should be noted that while less frequent activation of a control system (for example, through introducing delays or cycle restrictions) would diminish

13. In general, compared to electrochromics, the power consumption is higher for liquid crystals because of the need for continuous power in the activated state [Lampert, 1995].

the attention drawn to it (i.e., the occupant's attention) and increase its longevity, particularly if there is a mechanical system involved (with possible noise), as in motorized Venetian blinds, this should be designed with care. If the time step is unreasonably lengthened, the control system may not fully achieve its control objectives. Clearly, this is due to the large variation in daylight availability and solar radiation caused by diurnal and seasonal changes in the sun position and cloud cover.

Currently, of all the dynamic/smart facade technologies, automated blinds, electrochromic glazing and building-integrated photovoltaics are, in varying degrees, considered to be in more advanced states of development and more promising for commercial applications in the near future than the other innovative technologies mentioned above. These technologies and their anticipated impact on the luminous environment and lighting energy demand in office buildings have been the focus of this study. As shown in the following chapters, methods were devised in order to evaluate their performance, assess their possible interactions with other building systems, and investigate the means for optimizing the potential benefits of their integration into today's office buildings. In other words, the notion of controlling daylight admission through the transparent area of the building envelope by varying the transmittance of the glazing or using automatic shading devices, coupled with the operation of daylight-linked lighting controls, was utilized to investigate the possibility of improving the luminous environment in non-domestic buildings for a significant fraction of the working year while minimizing energy use. In addition, the notion of incorporating electricity-generating devices (i.e., photovoltaics) into the opaque area of the building envelope was utilized to investigate the potential energy benefits of such an integration and quantify the expected contribution to further reducing the electric energy load of the building. Quantifying the systems' performance was based on time-varying internal illuminance and energy values predicted as functions of real time-varying meteorological conditions, facade orientations, device properties, and implementation strategies.

Chapter

3

Modelling Time-Varying Illuminances

"He jests at scars, that never felt a wound.
But, soft! what light through yonder window breaks?
It is the east, and Juliet is the sun."

WILLIAM SHAKESPEARE 1564-1616 (*ROMEO AND JULIET*, ACT II, SC. II)

Before undertaking the assessment of the illuminance and energy performance of innovative fenestration devices, it was first necessary to review the daylight calculation methods currently in use in order to select the modelling approach to adopt/embrace which could provide sufficient accuracy, realism, and versatility to the study. This is addressed in the current chapter.

3.1 Daylight Modelling

Several approaches have been developed for determining the relationship between the daylight outside and the amount of natural light within a building. Daylight prediction techniques are based on either manual calculations, scale model photometry, or computer simulations. They have varying degrees of accuracy and realism, depending on the assumptions and limitations of the approach used. While simple manual daylight prediction methods can be used as a preliminary stage in assessing the visual and energy impacts of window design, more complex sky modelling techniques can be used in computer programs to predict more accurately electric lighting use and energy consumption in buildings [BRE, 1986]. The internal illuminance is usually evaluated at workplane height, 0.75 - 0.8 m., where the majority of tasks take place [Glaser et al., 2002].

3.1.1 Conventional Methods: Daylight Factors

The daylight performance of a building has been traditionally characterized using the daylight factor (DF) approach. The daylight factor at any point in a building is the ratio of the internal illuminance at that point, E_{inside}, to the global horizontal illuminance, $E_{outside}$, under CIE[1] standard overcast sky conditions, Figure 3-1. It can be measured in a scale model using an

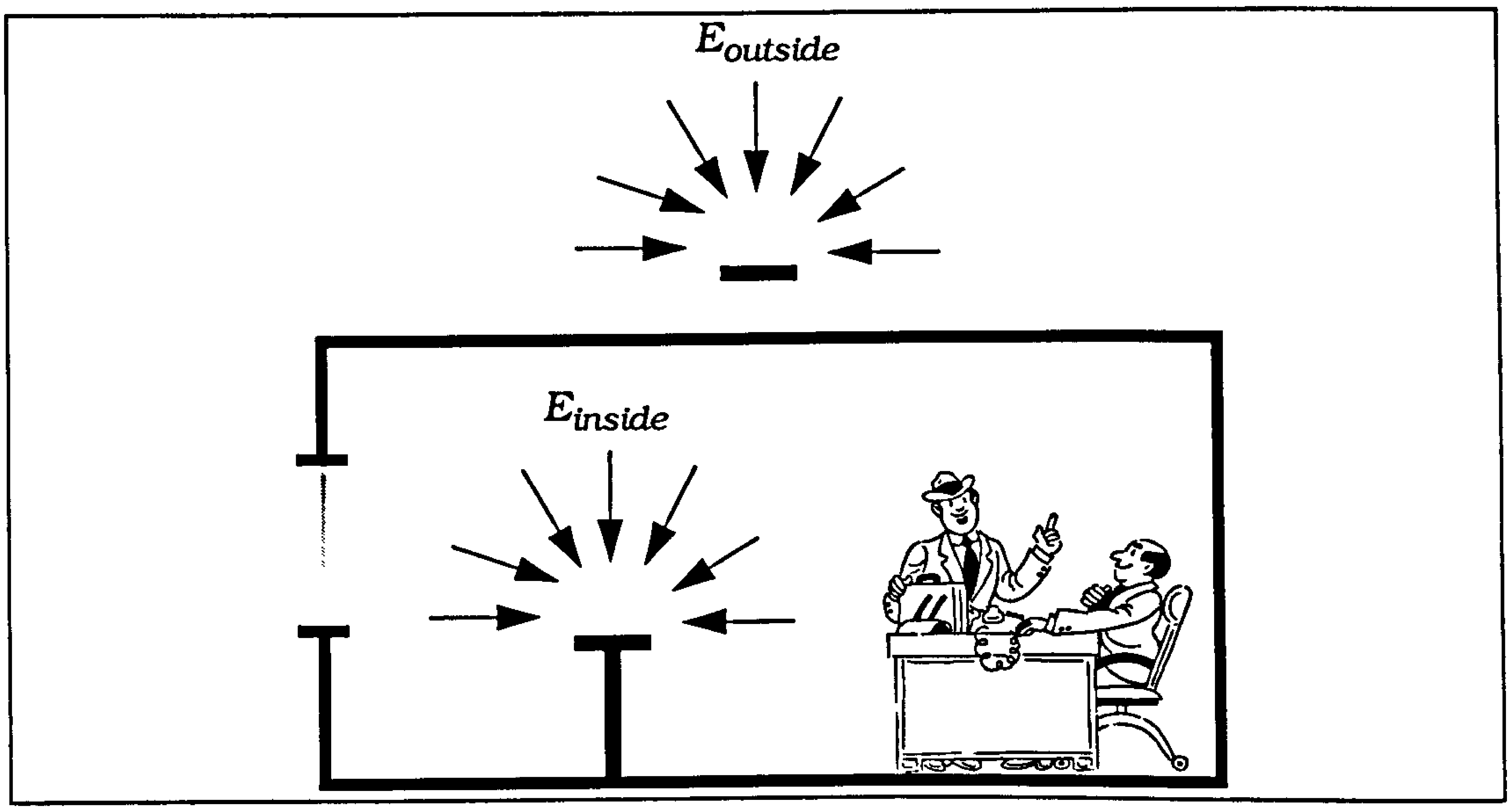

Figure 3-1 Internal and external horizontal illuminance

artificial sky, manually calculated using tables, diagrams, and protractors,

1. The Commission Internationale de l'Eclairage (CIE) sets the international standards for lighting, daylight, and colour measurement and estimation.

or easily obtained using simple computer programs. It is normally expressed as a percentage as follows:

$$DF = \frac{E_{inside}}{E_{outside}} \times 100\% \qquad \textbf{(3-1)}$$

This approach excludes the contribution of sunlight (direct and indirect) from the calculation since it uses the standard overcast sky. In addition, the daylight factor cannot account for the effects of building orientation since the luminance of the standard overcast sky does not vary with azimuth. Although this significantly simplifies the calculation of internal daylight levels, the CIE overcast sky is an extreme sky condition representative of only a limited number of naturally occurring real skies. Thus, the daylight factor should generally be recognized as an indication of daylight illumination on dull days, which ignores the time-varying nature of real sky conditions. Moreover, while the daylight factor method references the internal illuminance to the global horizontal illuminance outside, empirical results from some studies have shown that daylight levels in a side-lit room may actually be more nearly proportional to the amount of daylight falling on the window (i.e., incident on the vertical plane), rather than to the external horizontal daylight illuminance [Li et al., 2001].

While the limitation of the daylight factor approach may be tolerated for coarse calculations, it would be considered insufficiently accurate for a detailed assessment of the energy balance of a daylit room or an investigation of the illuminance distribution inside [Tregenza et al., 1983]. In order to realistically represent natural internal illuminance, actual meteorological conditions need to be taken into consideration. Nevertheless, time-varying sky and sun conditions are usually unaccounted for in conventional approaches developed for predicting daylight inside a building. Not only would a realistic prediction approach need to take into account those time-varying naturally occurring sun and sky conditions, it would also need to cover a time-series of, ideally, a full year and have the capability of indicating long term as well as short term variations in illuminance. Since modelling several thousand individual sun and sky conditions (i.e., hourly for one year) is computationally demanding, a need existed for a more practical alternative. While it may be possible to use advanced raytracing software packages (such as *Radiance*[2]) and reduce the number of sky conditions to be modelled by unifying/fusing the hours with similar (or near similar) sun positions and insolation levels, a more versatile approach is to use daylight coefficients, as described in the following sections.

3.1.2 Advanced Methods: Daylight Coefficients

The amount of daylight that falls on a surface in a room is regarded as dependent on two factors, which for most practical purposes are considered independent of each other: the luminance of the sky (and sun), and the structure and materials of the surrounding surfaces [Tregenza et al., 1983]. The sky luminance can vary independently from one angle of view to another. In addition, the illuminance inside a room is not equally sensitive to variations in the brightness of different parts of the sky. For example, the area visible through a window has a much bigger impact on the internal illuminance than other parts of the sky, which contribute to the illuminance only through reflection.

As such, the daylight coefficient (DC) approach depends on the idea of dividing up the sky into a large number of very small elements or patches and considering each element on its own. The contribution to the internal illuminance made by every element of sky is calculated separately, and the total illuminance is then determined by summing the contributions from all the sky elements [Tregenza et al., 1983].

In computer simulations, this approach can speed up daylight calculations since it eliminates the need to repeat the inter-reflection calculation, the

2. *Radiance* is a backward raytracer, which blends deterministic and stochastic raytracing techniques to solve light transfer. The program was developed by Greg Ward (aka Greg Ward Larson) at Lawrence Berkeley National Laboratories and yields physically-based photo-realistic simulations of indoor illuminance and luminance distributions for diffuse, specular and partly specular material surfaces [Ward Larson et al., 1998].

most time-consuming and computationally demanding part of the simulation, for every individual sky luminance distribution [Mardaljevic, 2000a]. Once a set of daylight coefficients has been calculated for a proposed design of a building, for instance, it is possible to compute the internal illuminance under a large number of sky luminance distributions with minor extra effort [Littlefair, 1992]. Therefore, the daylighting performance of a building can be studied for a whole year of time-varying sky and sun conditions, and provided the number of sky elements is less than that of daylight hours in a year, the technique has the potential to be computationally more efficient than treating each sky individually [Mardaljevic, 2000a].

If $\Delta E_{\gamma\alpha}$ is the total illuminance produced at a point in a room by a small element of sky at altitude γ and azimuth α, then the daylight coefficient is defined as follows:

$$D_{\gamma\alpha} = \frac{\Delta E_{\gamma\alpha}}{L_{\gamma\alpha}\,\Delta S_{\gamma\alpha}} \tag{3-2}$$

where $L_{\gamma\alpha}$ is the luminance of the element of sky, and $\Delta S_{\gamma\alpha}$ is the solid angle of that element, Figure 3-2. The magnitude of the daylight coefficient, $D_{\gamma\alpha}$,

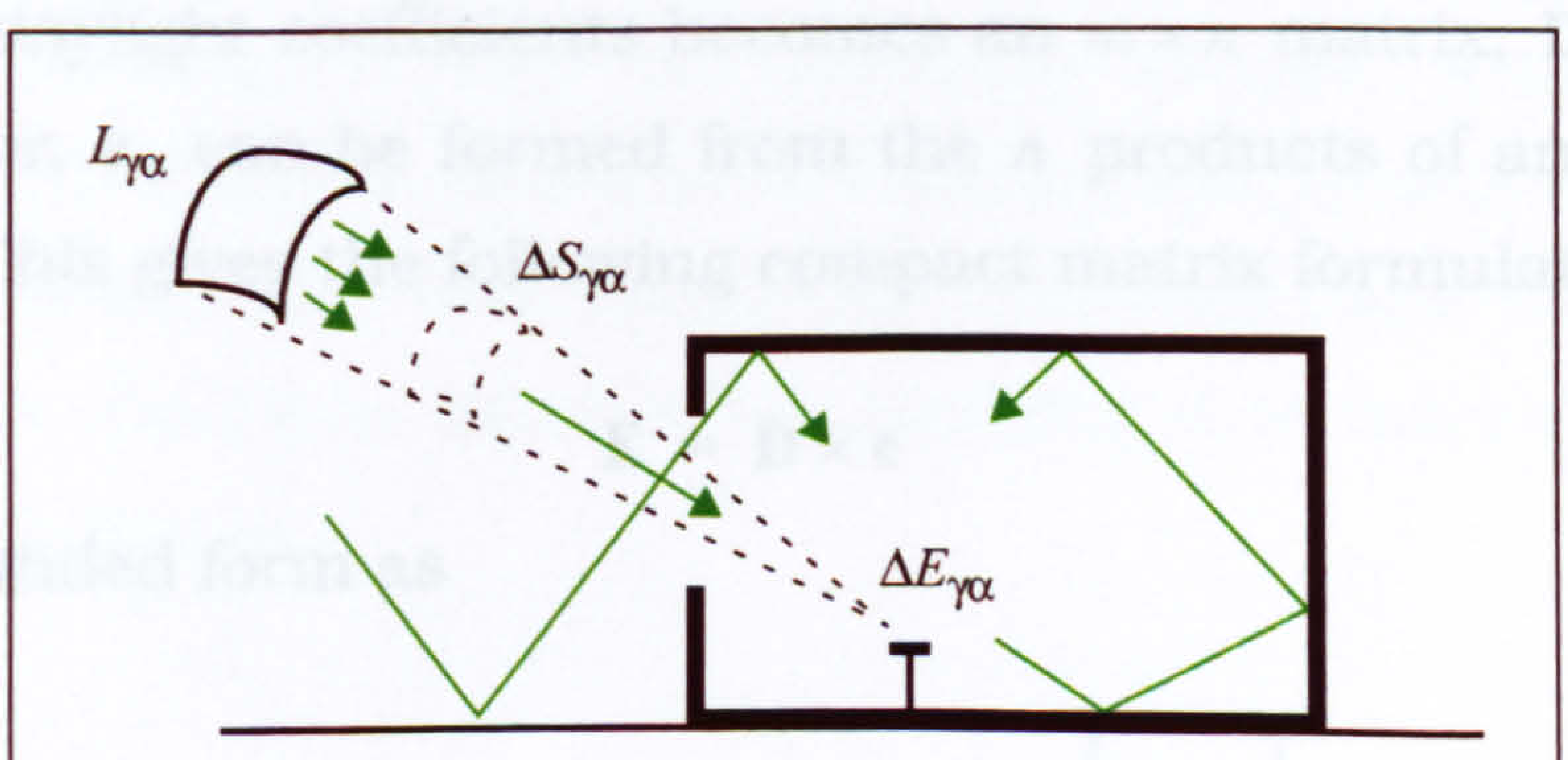

Figure 3-2 Daylight coefficient basics [re-drawn from Mardaljevic, 2000b]

Illuminance $\Delta E_{\gamma\alpha}$ accounts for all the direct and inter-reflected light from the sky patch at (γ,α)

will depend on the physical characteristics of the room and the external environment, for example, room geometry, surface reflectances, glazing transmissivity, outside obstructions and reflections, etc.. It is, however, independent of the distribution of luminance across the sky vault since $\Delta E_{\gamma\alpha}$ varies in proportion to $L_{\gamma\alpha}$ [Tregenza et al., 1983].

The total illuminance E produced at a point in a room is then given by

$$E = \int_0^{2\pi} \int_0^{\pi/2} D_{\gamma\alpha} L_{\gamma\alpha} \cos\gamma d\gamma d\alpha \qquad (3\text{-}3)$$

For any realistic scene, a finite element calculation will be required to solve the integral. If the sky is divided into n angular zones or patches, the illuminance can be given as the sum of n products of D, S, and L for each patch of sky p. The total illuminance, E, produced at that point in the room is then given by [Tregenza et al., 1983]

$$E = \sum_{p=1}^{n} D_p S_p L_p \qquad (3\text{-}4)$$

The n values of D, S, and L can, therefore, be treated as vectors. If the formulation is expanded to account for m points in the room, the internal illuminance will be described by a column vector, $\mathbf{E}$, containing m elements, the array of daylight coefficients becomes an $m \times n$ matrix, $\mathbf{D}$, and another column vector, $\mathbf{c}$, can be formed from the n products of angular size and luminance. This gives the following compact matrix formulation

$$\mathbf{E} = \mathbf{D} \times \mathbf{c} \qquad (3\text{-}5)$$

or in an expanded form as

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_m \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & \dots & D_{1n} \\ D_{21} & D_{22} & \dots & D_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ D_{m1} & D_{m2} & \dots & D_{mn} \end{bmatrix} \times \begin{bmatrix} S_1 & L_1 \\ S_2 & L_2 \\ \vdots & \vdots \\ \vdots & \vdots \\ S_n & L_n \end{bmatrix} \qquad (3\text{-}6)$$

Here, an assumption is made that the internal distances between the calculation points are very small in comparison with those between the points and the elements of sky so that a sky element subtends effectively the same angle from all the points in the room [Tregenza et al., 1983]. This is a perfectly reasonable assumption for models on the scale of buildings.

3.1.3 DC Implementations

As gathered from the literature and until the time of writing, the basic daylight coefficient approach has featured in three reported implementations. They are described below.

ESP-r

In *ESP-r*[3], a Unix-based integrated modelling tool, the sky hemisphere is divided into 145 circular elements and a daylight coefficient is calculated for each element. A link to *Radiance* is then employed so that the internal illuminance distribution can be determined, whereby each total illuminance value is the summation of the time-dependent diffuse sky illuminance and direct sun illuminance (the same set of daylight coefficients is used for direct and diffuse light). This implementation was validated by Janak et al. against *Radiance*'s standard calculation, and it was concluded that although the method gave satisfactory results for the most common of building geometries, it was not generally robust, with large errors introduced by the direct illuminance contribution [Janak et al., 1999]. It was thus recommended that the method still had room for improvement and that care should be taken when applying it to more complex room/ facade configurations.

3. ESP-r has been developed at the University of Strathclyde in Glasgow, Scotland, for the simulation of the thermal, visual, and acoustic performance of buildings and the assessment of the energy use and gaseous emissions associated with the environmental control systems and constructional materials [ESRU, 2002].

DAYSIM

At a progressed stage of this study, information was made available about a DC/*Radiance* implementation developed by a fellow researcher at the Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany [Reinhart et al., 2001]. Only a brief review, rather than an extensive investigation, of this implementation was conducted. In *DAYSIM*[4], the sky hemisphere is divided into 145 circular elements, and the calculated 145 daylight coefficients are used for obtaining the contribution to illuminance from diffuse daylight. In order to obtain the contributions from external ground reflections, 3 additional ground daylight coefficients are introduced by partitioning the ground hemisphere into 3 ground elements (segments). Contributions from direct sunlight to internal illuminance are modelled using approximately 65 sun positions, which are a subset of all possible sun positions throughout the year, for which ~65 direct sunlight coefficients are calculated. This implementation has undergone some limited validation [Reinhart, 2001].

XDAPS

The XDAPS (eXtensible DAylight Prediction System) formulation of calculating daylight coefficients and illuminance using the Unix-based *Radiance* lighting simulation system and custom-written routines was developed by Mardaljevic at the IESD, De Montfort University, Leicester, UK. It was validated under real sky conditions using the BRE-IDMP[5] dataset and proven to be highly accurate [Mardaljevic, 2000b]. The skies in the

4. *DAYSIM* is a *Radiance*-based dynamic daylight simulation method, developed by C. Reinhart at the Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany and the Institute for Research in Construction, Canada, to calculate the short time-step development of indoor illuminances in buildings, based on hourly mean direct and diffuse irradiation values [IRC, 2002]

5. A total of 754 simultaneous measurements of internal illuminance and sky luminance were collated by Mardaljevic into a dataset, referred to as the BRE-IDMP dataset, for the validation of illuminance predictions from lighting simulation. These collated measurements were from a sky monitoring study carried out at the Building Research Establishment (BRE) during 1992 and 1993 as part of the BRE contribution to the International Daylighting Measuring Programme (IDMP) [Mardaljevic, 2000c].

validation dataset were regarded as containing much of the variation that might be expected in a UK Test Reference Year (TRY) and covering a wide range of naturally occurring sky conditions from heavily overcast, through intermediate to clear. Details of the validation process can be found in several of the developer's publications [Mardaljevic, 2000b][Mardaljevic, 2001]. Although the XDAPS formulation is the most complex of all three implementations[6], it is the one that has been most rigorously validated, and therefore, it was the engine utilized for the purposes of this study, as detailed in the following sections.

3.2 Daylight Coefficients and the XDAPS *Radiance* Implementation

The detail of the XDAPS formulation was partly dictated by *Radiance*'s own unique calculation algorithms. It requires that three different daylight coefficient matrices (DCMs) be computed using programs custom-written in IDL (Interactive Data Language) and Unix C-shell. A DCM is specific to a proposed design and would need to be re-computed if significant modifications are introduced to the physical properties of the building or its surroundings.

The implementation then uses custom-written data analysis programs to derive internal illuminance from the DCMs. The total internal illuminance, E, due to a sky and sun of arbitrary luminance, is computed as the sum of four illuminance components,

$$E = E^d_{sky} + E^i_{sky} + E^d_{sun} + E^i_{sun} \tag{3-7}$$

where E^d_{sky} and E^i_{sky} are the direct and indirect components of illuminance due to the sky, respectively, while E^d_{sun} and E^i_{sun} are the direct and indirect components of illuminance due to the sun, respectively. The direct components of illuminance account for the window and room configuration, external obstructions, and glazing transmittance. The indirect components

6. Note that *Radiance* was used in all three implementations.

account for inter-reflected light, both inside and outside the room. Each of these four components can be defined in terms of a daylight coefficient matrix (DCM) and a product of source angular size and source luminance. A description of how they are predicted is given in the following sections and the diagrams in Figure 3-3.

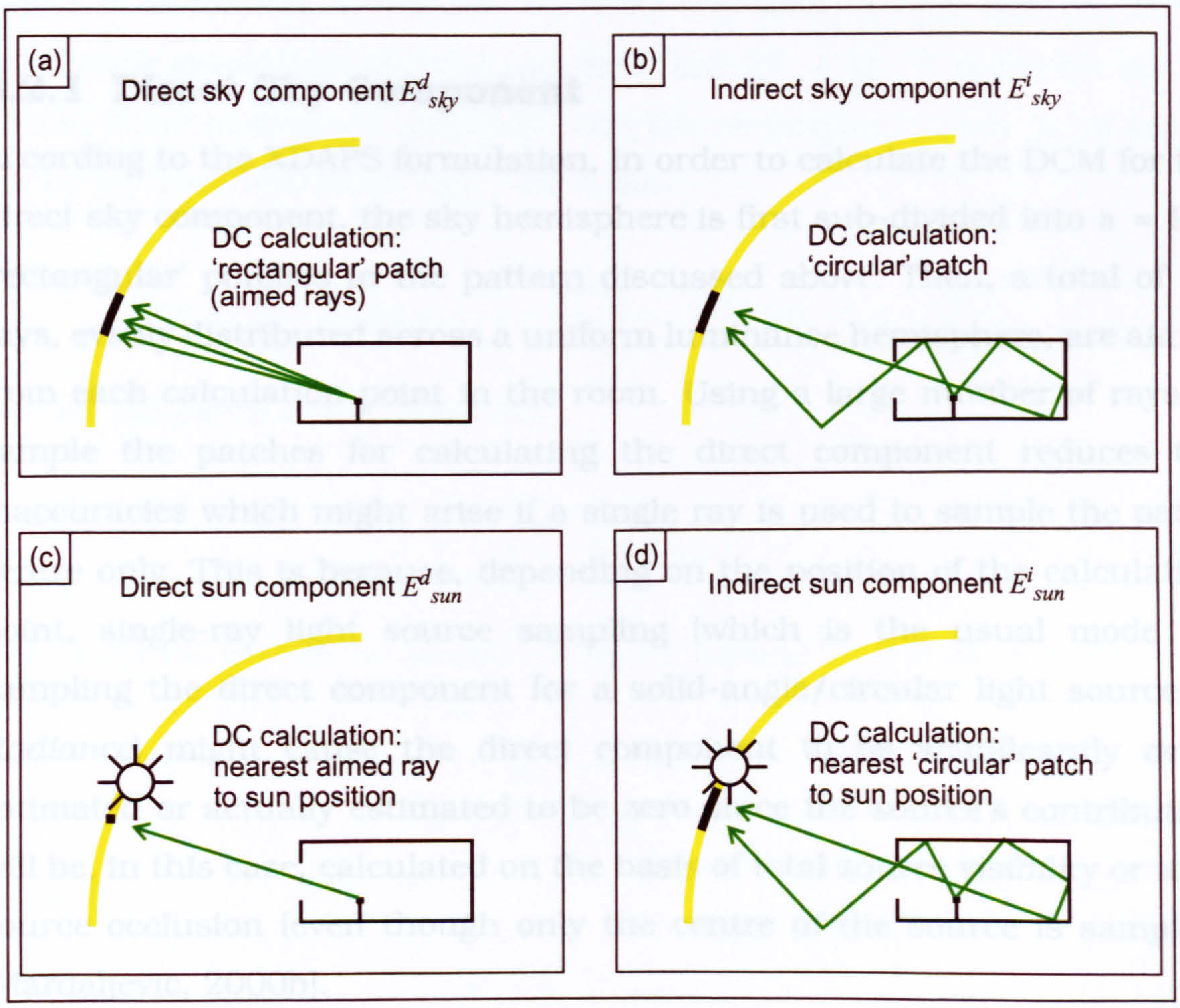

Figure 3-3 The four components of illuminance [Mardaljevic, 2000b]

It should be first noted that when this formulation was developed, the intention was to evaluate the accuracy of the illuminances derived using DCs against the BRE-IDMP validation dataset. Hence, the incorporated sky discretisation schemes had to correspond to the sampling pattern of the sky scanner employed in the data measurements. One of these schemes, which gave complete coverage of the sky hemisphere with no overlap, was based on the partition of the sky into 145 'rectangular[7]' patches, with each patch defined by lower and upper values for altitude and azimuth. The other type of discretisation used solid angles, i.e., 145 'circular' patches. Similar to the pattern of the sky scanner, both patch schemes were numbered in a clockwise direction starting from north, on the edge of the hemisphere and moving towards the centre such that patch #145 was the 'polar cap' [Mardaljevic, 2000b].

3.2.1 Direct Sky Component

According to the XDAPS formulation, in order to calculate the DCM for the direct sky component, the sky hemisphere is first sub-divided into $n = 145$ 'rectangular' patches in the pattern discussed above. Then, a total of N_r rays, evenly distributed across a uniform luminance hemisphere, are aimed from each calculation point in the room. Using a large number of rays to sample the patches for calculating the direct component reduces the inaccuracies which might arise if a single ray is used to sample the patch centre only. This is because, depending on the position of the calculation point, single-ray light source sampling (which is the usual mode for sampling the direct component for a solid-angle/circular light source in *Radiance*) might cause the direct component to be significantly over-estimated or actually estimated to be zero since the source's contribution will be, in this case, calculated on the basis of total source visibility or total source occlusion (even though only the centre of the source is sampled) [Mardaljevic, 2000b].

It should be noted that the 'aimed rays' approach requires only one sky vault description. There is no theoretical limit to the number of rays, and a sensitivity analysis is used to decide on the number beyond which no noticeable improvement in the sampling of the patches is achieved. In this study, a total of 38,316 rays are used so that each patch is sampled by

7. Although these elements of sky were in fact parts of a hemisphere, they were called 'rectangular' patches for simplicity.

approximately 264 rays, $\left(\frac{38316}{145} \approx 264\right)$. The illuminance at a point in the room due to any patch of sky is then determined from the individual luminance values returned by all the rays that intersect that particular patch. The illuminance due to the sky patch, p, is given by

$$\Delta E_p = \sum_{r \in T} L_r \cos\theta_r \Delta S_r \tag{3-8}$$

where L_r is the ray luminance, θ_r is the ray zenith angle, and ΔS_r is the solid angle associated with the ray such that $\Delta S_r = \frac{2\pi}{N_r}$. T is the set of rays r that, if not obstructed, intersect with the rectangular patch, p, of extent $\Delta\alpha$ by $\Delta\gamma$ and centred on (α,γ), such that

$$T = \left\{r:\left(\gamma - \frac{\Delta\gamma}{2}\right) \le \gamma_r < \left(\gamma + \frac{\Delta\gamma}{2}\right), \left(\alpha - \frac{\Delta\alpha}{2}\right) \le \alpha_r < \left(\alpha + \frac{\Delta\alpha}{2}\right)\right\} \tag{3-9}$$

and for the patch at the 'polar cap',

$$T = \left\{r:\left(\frac{\pi}{2} - \Delta\gamma_z\right) \le \gamma_r\right\} \tag{3-10}$$

The direct DC is then computed using Eq 3-2 and Eq 3-8 as follows:

$$D_p = \frac{\sum_{r \in T} L_r \cos\theta_r \Delta S_r}{L_p \Delta S_p} \tag{3-11}$$

Since

$$\sum_{r \in T} \Delta S_r = \Delta S_p \tag{3-12}$$

then

$$D_p = \frac{\sum_{r \in T} L_r \cos\theta_r}{L_p} \tag{3-13}$$

The direct sky illuminance is the result of multiplying the direct DCM by the vector product of the angular size and luminance of the rectangular sky patches.

3.2.2 Indirect Sky Component

In order to calculate the indirect sky DCM, the sky hemisphere is first sub-divided into $n = 145$ 'circular' patches defined using solid angles. Each of these circular patches is then considered in turn independently as the sole source of light, of source angle 11°. To calculate the illuminance at a point due to a circular patch source in *Radiance*, as mentioned earlier, that source is sampled with a single ray directed from the point to the source centre for the direct component, and for the indirect component, after many sampling rays, the final light transfer from a surface to the source is again a single ray to the source centre. The DC due to a circular patch, p, is then given by

$$D_p = \frac{\Delta E_{p(c)}}{L_{p(c)} \Delta S_{p(c)}} \tag{3-14}$$

The difference between the total DC and the direct DC is taken as the indirect component due to the sky.

Using these circular patches sampled just at their centres is less likely to be a problem for the indirect sky component than for the direct one since for the indirect component, many sampling rays from many different ray origins are used in the calculation. Although this circular sub-division of the sky does not offer complete sky coverage, the source angle has no effect because only the centre of the circular sky source is sampled. Since the indirect component arises from one or more reflections (i.e., it is less directional in nature than the direct component), hence the difference between a point and a patch indirect DC is not likely to be so significant. It should also be added that it is not possible to specify a rectangular source angle in *Radiance* [Mardaljevic, 2000b].

Although circular patches (subscript c) are used in calculating the DCM, the indirect sky illuminance is the result of multiplying that indirect DCM by the vector product of the angular size and luminance of the rectangular sky patches (subscript r). This is because the sum of the individual patch solid angles must be equal to the solid angle of a hemisphere, i.e.,

$$2\pi = \sum_{p=1}^{n} \Delta S_{p(r)} \tag{3-15}$$

3.2.3 Direct Sun Component

Analogous to the direct sky component, the direct sun component is sensitive to potentially significant over- or under-estimation errors due to single-ray light source sampling. This may arise when there is a large difference between the actual sun position and the centre of the nearest patch (sun displacement angle[8]). The larger the sun displacement angle, the larger the possibility that a point is estimated to be in the shade when it is actually in the sun or vice versa. Hence, the direct component of sun illuminance is the most susceptible to be in error [Mardaljevic, 2000b].

However, similar to the direct sky component, these errors can be reduced arbitrarily by using a large number of sources for the direct component only, i.e., aimed rays [Mardaljevic, 2000b]. Therefore, using *Radiance*, a total of 5,056 rays, evenly distributed across a uniform luminance hemisphere, are aimed from each calculation point in the room. The luminance values returned by the rays are then used to construct the direct DCM for all the evenly distributed 5,056 points where the rays intersect the hemisphere. The illuminance due to a ray, r, is given by

$$\Delta E_r = L_r \cos\theta_r \Delta S_r \tag{3-16}$$

and the direct DC can be given by

$$D_r = \frac{L_r \cos\theta_r \Delta S_r}{L_p \Delta S_r} \tag{3-17}$$

i.e.,

8. With a patch discretisation based on the scanner pattern, the sun displacement angle with single-ray light source sampling can be as large as 7°. [Mardaljevic, 2000b]

$$D_r = \frac{L_r \cos\theta_r}{L_p} \tag{3-18}$$

Of the 5,056 points on the hemisphere, the point closest to the actual sun position is located[9], and the column vector, δ, corresponding to this point in the 'm x 5056' matrix is multiplied by the sun solid angle and luminance in order to produce the direct illuminance due to the sun.

3.2.4 Indirect Sun Component

Similarly, referring to the 145-patch DCM calculated for the indirect sky component, the circular patch whose centre is closest to the actual sun position is located, and the column vector β corresponding to this patch in the 'm x 145' matrix is multiplied by the sun solid angle and luminance in order to produce the indirect illuminance due to the sun. As with the indirect sky component, since the indirect sun component is less directional in nature than the direct component (i.e., arising from one or more reflections), it is generally less sensitive to the sun displacement angle and errors that might arise from single-ray light source sampling.

3.2.5 Total Illuminance

The total internal illuminance in Eq 3-7 (and Figure 3-3) can then be expressed in terms of daylight coefficient matrices as follows:

$$\mathbf{E} = (\mathbf{D}^{d145} \times \mathbf{c}^{145}) + (\mathbf{D}^{i145} \times \mathbf{c}^{145}) + \mathbf{D}_{\delta}^{d5056} S^{sun} L^{sun} + \mathbf{D}_{\beta}^{i145} S^{sun} L^{sun} \tag{3-19}$$

where the column vector, $\mathbf{c}^{145}$, is formed from the 145 products of angular size and luminance, $\mathbf{D}^{d145}$ is the direct sky DCM, $\mathbf{D}^{i145}$ is the indirect sky DCM, $\mathbf{D}_{\delta}^{d5056}$ is the DC vector for the ray closest to the sun position, $\mathbf{D}_{\beta}^{i145}$ is the DC vector for the patch closest to the sun position, and the scalars S^{sun} and L^{sun} are the solid angle and luminance of the sun, respectively.

9. Since a 5,056 patch DCM is a much finer discretisation than 145, the displacement between the actual sun position and that of the nearest patch is minimized [Mardaljevic, 2000c]

3.3 Daylight Modelling

As mentioned earlier, the XDAPS formulation was the engine utilized for calculating daylight coefficients and deriving irradiances and illuminances for the purposes of this study. The following sections include the application of the formulation on an office model and the illustration of the obtained results, in preparation for the analysis metrics introduced in Chapter 4.

3.3.1 Office Model

A simple model of a typical office was constructed using *Radiance* scripts and surface generators. The dimensions were as follows: 3 m. width, 6 m. depth, and 2.7 m. height. A window of 3 m. width, 1.95 m. height, and 0.75 m. sill height was 'fitted' into one of the smaller sides of the office as shown in Figure 3-4.

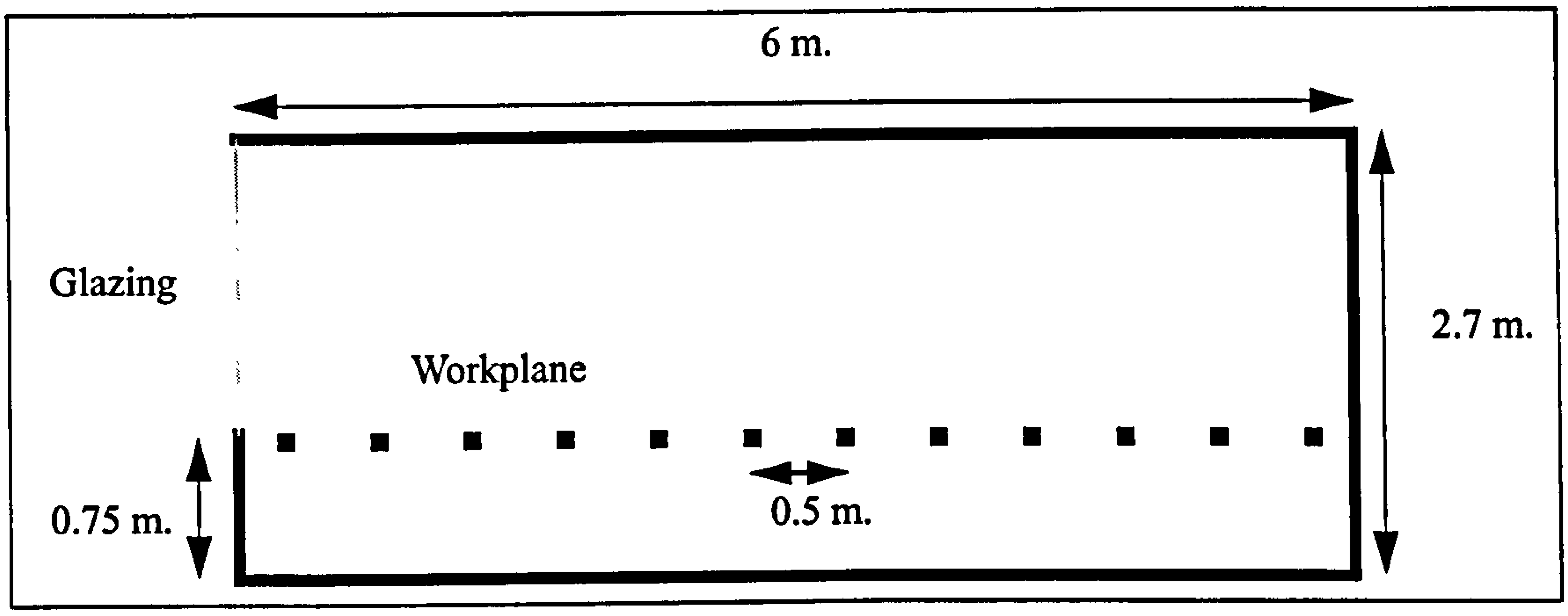

Figure 3-4 Model dimensions

A side-lit private office (i.e., in a cellular building) with these dimensions was selected as the model for several reasons. First, this type of office is apparently becoming preferable again after nearly three decades of emphasis on open-plan office workplaces [Sweitzer, 1991]. Second, compared to their earlier counterparts, today's private perimeter offices throughout Europe are often smaller, longer, and narrower in proportion, in order to optimize the number of office units in a building with window exposures. Third, private offices are believed to offer a bigger potential for the control of daylighting and electric lighting to satisfy personal preferences as well as task needs [Sweitzer, 1991].

It should be pointed out that the window sill in the office model was placed at the same level as the workplane (desk level) on which the light was needed (at 0.75 m. high from the floor) and not any lower. Since daylight entering the office below the workplane must be reflected at least twice before reaching this level, the reflectance of the floor is usually lower than the reflectance of the other interior surfaces, and the desks and tables (and other horizontal surfaces) in the office prevent part of this reflected daylight from reaching above the desk level, therefore, any facade area below the desk level would be considered as contributing very little to the workplane illuminance [Vartiainen et al., 2000].

The reflectivities of the walls, ceiling, and floor in this typical office model were set to be 0.7, 0.8, and 0.2, respectively. The window was assumed to have standard 6 mm. clear double glazing with transmittance[10] of 0.76 [Pilkington, 1991]. To account for external ground reflections, a ground plane of dimensions 11 m. by 15 m. was placed on the outer side of the window wall, with its shorter side adjacent to the wall. The reflectivity of the ground plane was set at 0.2.

3.3.2 TRY Irradiation Data

The hourly solar irradiation data from Kew-84 (51.47°N, 0.28°W) Test Reference Year (TRY), used to derive the hourly sky and sun conditions as detailed in the following section, consisted of values of diffuse horizontal irradiation and direct normal irradiation for each of the 8,760 hours in the

10. Transmissivity of a glass plate is the fraction of light that passes through the glass at normal incidence while transmittance is the total light transmitted through the glass. The latter depends on the index of refraction and is always less than the former since additional light is reflected at each interface. Although transmittance is more easily measured, mathematically, it is more convenient to work with transmissivity [Ward Larson et al., 1998]. Clear double glazing of 76% transmittance has a transmissivity of 82.8%.

year. These values are displayed in the form of '365 x 24' false colour matrices in Figure 3-5. Zero irradiation values are represented by a grey

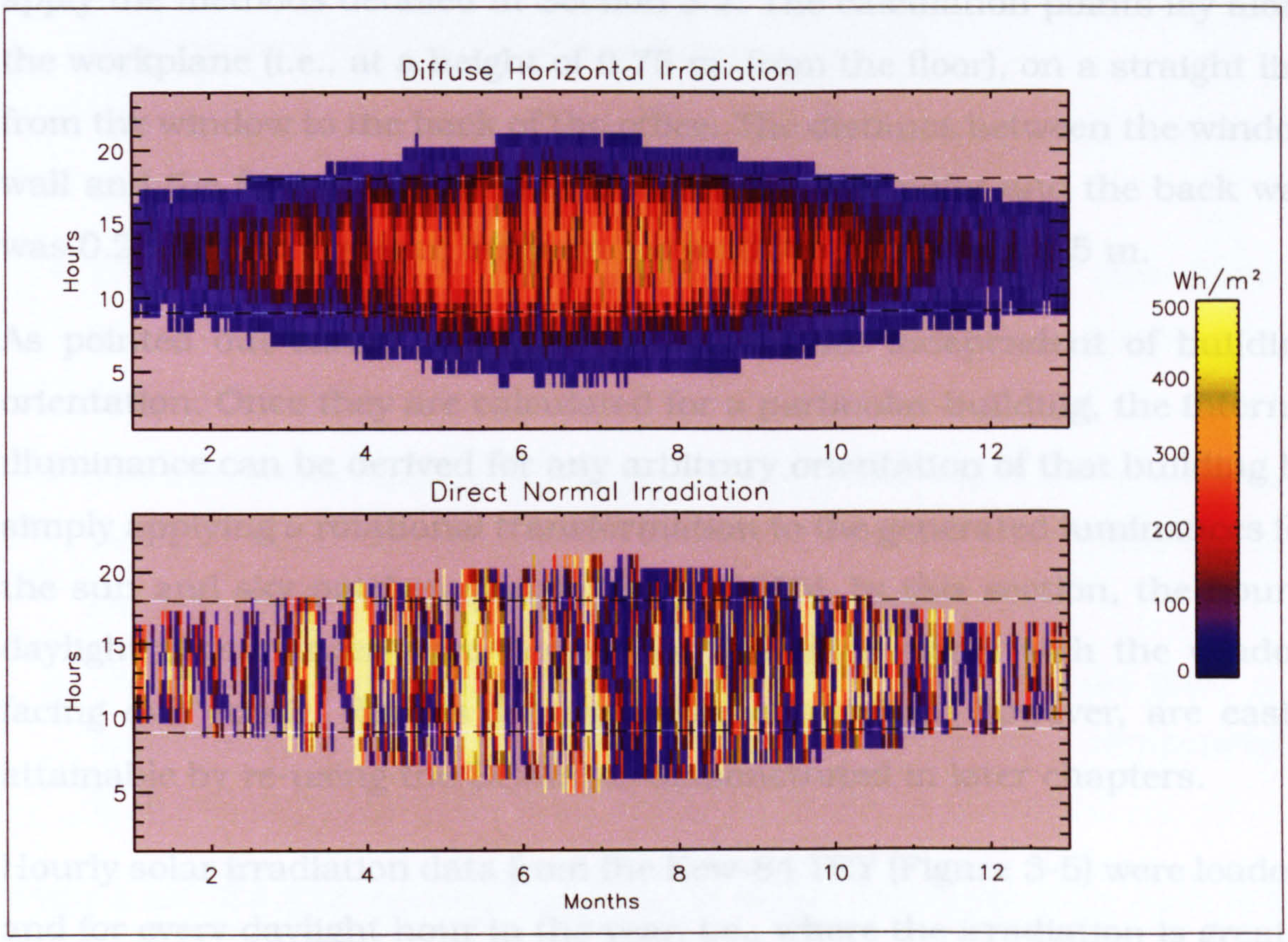

Figure 3-5 Irradiation components from Kew-84 TRY

colour while higher values are scaled ascendingly from blue to yellow. The two horizontal dashed lines denote the start and finish hours of a typical working day, for example, 09:00 and 18:00 hours. With the aid of this type of display, the seasonal as well as the hourly variations in irradiation can be easily appreciated. As seen in Figure 3-5, while the seasonal and daily variations are apparent in both components of irradiation, the hourly variations in the direct normal irradiation, in particular, are clearly visible.

3.3.3 Daylight Illuminance Derivation from DCs

Daylight coefficients were calculated for each of 12 points in the office model using a set of custom-written Unix C-shell scripts and IDL programs which apply the methods detailed in Section 3.2. The calculation points lay along the workplane (i.e., at a height of 0.75 m. from the floor), on a straight line from the window to the back of the office. The distance between the window wall and the first point and that between the last point and the back wall was 0.25 m. The distance between consecutive points was 0.5 m.

As pointed out earlier, daylight coefficients are independent of building orientation. Once they are calculated for a particular building, the internal illuminance can be derived for any arbitrary orientation of that building by simply applying a rotational transformation to the generated luminances for the sun and sky patches [Mardaljevic, 2000b]. In this section, the hourly daylight illuminances were derived for the office model with the window facing due south. Results for any other orientation, however, are easily attainable by re-using the DCMs, as demonstrated in later chapters.

Hourly solar irradiation data from the Kew-84 TRY (Figure 3-5) were loaded, and for every daylight hour in the year, i.e., where the irradiation is greater than zero (for this TRY, 4316 hours), the following was done:

- The sun position was calculated from the geographical position and time stamp of the TRY.
- Using a luminous efficacy of 120 lumens/watt, the irradiance was converted to illuminance, and the luminance of the sun was calculated. A simple constant value for the luminous efficacy was used in this study, but more complex models could be used if desired.
- The sky clearness index was calculated using the illuminance and the sun altitude.

- Using the illuminance and the sun position, a sky model was generated as a blend of the CIE standard overcast sky and the Matsuura intermediate sky model. A mixing factor based on the sky clearness index determined the relative proportions of overcast and intermediate sky used in the blended model[11].
- The luminances of each of the 145 sky patches were calculated from the sky model.
- The direct and indirect illuminances due to the sky were then derived using the corresponding DCMs and the angular size and luminance of each of the sky patches.
- The direct and indirect illuminances due to the sun were also derived using the corresponding DCM vectors (i.e., patches) closest to the sun positions and the solid angle and luminance of the sun.
- The total internal illuminance, due to the sky and sun, was then determined by the summation of those four illuminance components. This was carried out for each of the 12 points in the office.

While a set of 4,316 internal illuminance values was derived for each of the 12 calculation points in the office, for brevity, the hourly internal illuminances predicted for only one of the 12 points are displayed using false colours in Figure 3-6. The grey colour represents zero illuminance while higher daylight illuminance values are scaled ascendingly from blue to yellow. Similar to the hourly irradiance values in Figure 3-5, the hourly and seasonal variations in the internal illuminance at this particular point in the office are quite discernible.

Note that there were, in fact, '4316 x 12 x 4' (i.e., 207,168) internal illuminance values derived in the process since four components of

11. The mixing function for this sky blend was 'tuned' to the 754 skies in the validation dataset (used for validating the XDAPS formulation). Furthermore, on the basis of the Perez clearness index, the validation dataset skies were found to be reasonably representative of the range of skies in the Kew TRY. Thus, this sky blend can be considered to offer a credible approximation to the range of skies from which the Kew TRY was derived [Mardaljevic, 2000b].

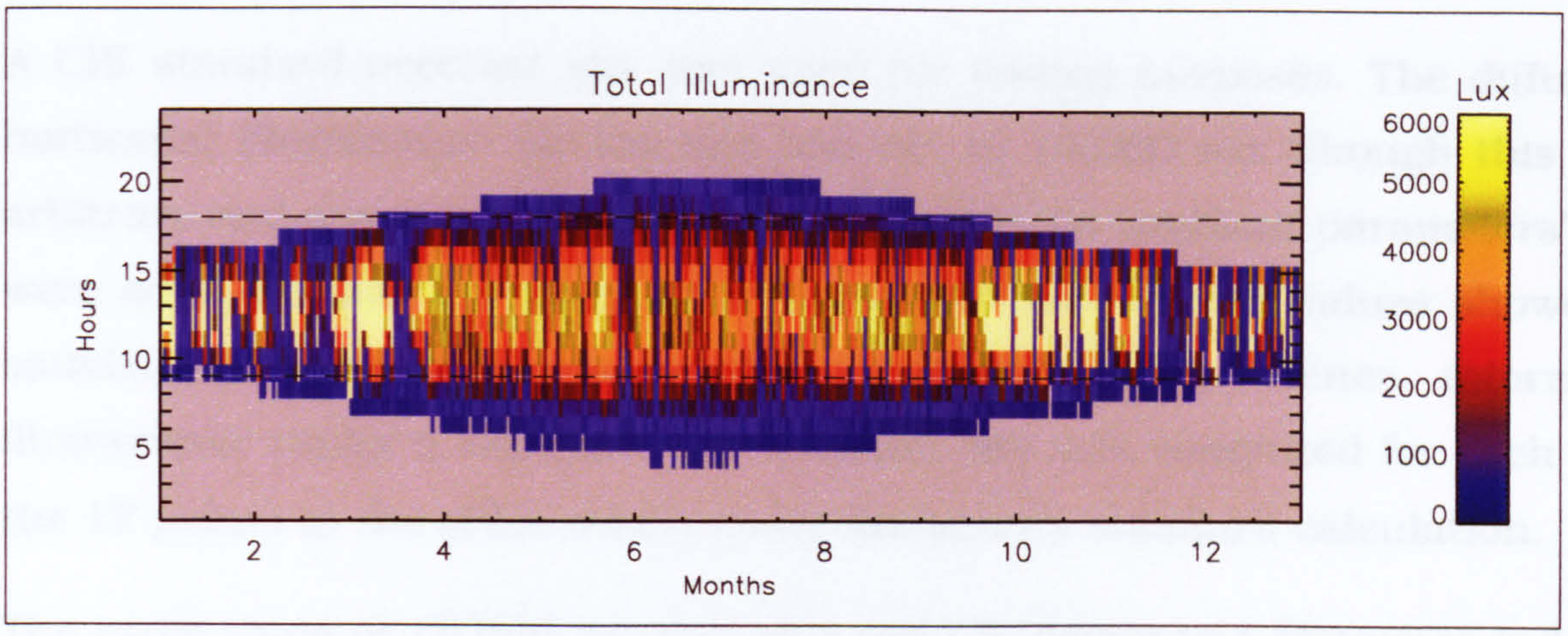

Figure 3-6 Total internal illuminance derived for a point on the workplane, 2.25m. from the window (facing due south)

illuminance were derived for each daylight hour for each point. Plots for each of the four components of illuminance were also generated, shown in Figure 3-7. As expected, the high daylight illuminance values distinct in the total illuminance plot in Figure 3-6, are recognized to be due to direct sun illuminance, particularly around midday during the winter months (from January until the middle of March and from the middle of September until the end of December).

3.4 Re-validation

The original XDAPS code in the implementation's custom-written routines, for calculating daylight coefficients and deriving daylight illuminance (previously validated by Mardaljevic), was modified in this study to allow the automation of simulations and introduce many new post-processing features. Hence, some re-validation testing was required in order to ensure that no 'bugs' were introduced into the programs. In the following section, a comparison is made between the daylight illuminance results obtained using the modified XDAPS routines and those obtained through the standard *Radiance* calculation. In Section 3.4.2, a comparison is made between irradiation values calculated using the XDAPS formulation and those obtained from a TRY file.

3.4.1 Daylight Coefficients and the Standard *Radiance* Calculation

A CIE standard overcast sky was used for testing purposes. The diffuse horizontal illuminance for the sky was set to 10,000 lux (though this is arbitrary and any value could be used). *Radiance*'s 'ambient parameters'[12] were adjusted and tuned until the calculated illuminance values showed satisfactory convergence at all the calculation points. Hence, internal illuminance under a standard CIE overcast sky was computed for each of the 12 points in the office model using *Radiance*'s standard calculation.

The same value of 10,000 lux was also used to compute a clearness index and a sky model with luminance values for the 145 sky patches using the modified XDAPS programs. No sun was included in the sky model, and no blending of skies was performed, i.e., the sky model was purely overcast. The direct and indirect illuminances for the 12 calculation points were then derived using the corresponding DCMs and the angular size and luminance of each of the sky patches. The daylight illuminance results are displayed in Figure 3-8.

It can be perceived from the figure that the internal illuminance values computed using the XDAPS formulation with the modified routines compare favourably with those of the standard *Radiance* calculation, with only slight under-predictions in the front half of the office. The mean bias error[13] (MBE) was calculated to be -3.8%, the root mean square error (RMSE) 4.1%, and the maximum relative error (RER) -6.8%.

3.4.2 Daylight Coefficients and TRY Data

In order to assess the accuracy of irradiation values predicted using the daylight coefficient approach and the XDAPS formulation, hourly

12. The ambient parameters are the key simulation parameters for daylight illuminance calculations in the *Radiance* system. They control the number of reflections and the resolution of the inter-reflection calculation [Mardaljevic, 2000b].

13. See Section A.1 for error analysis equations.

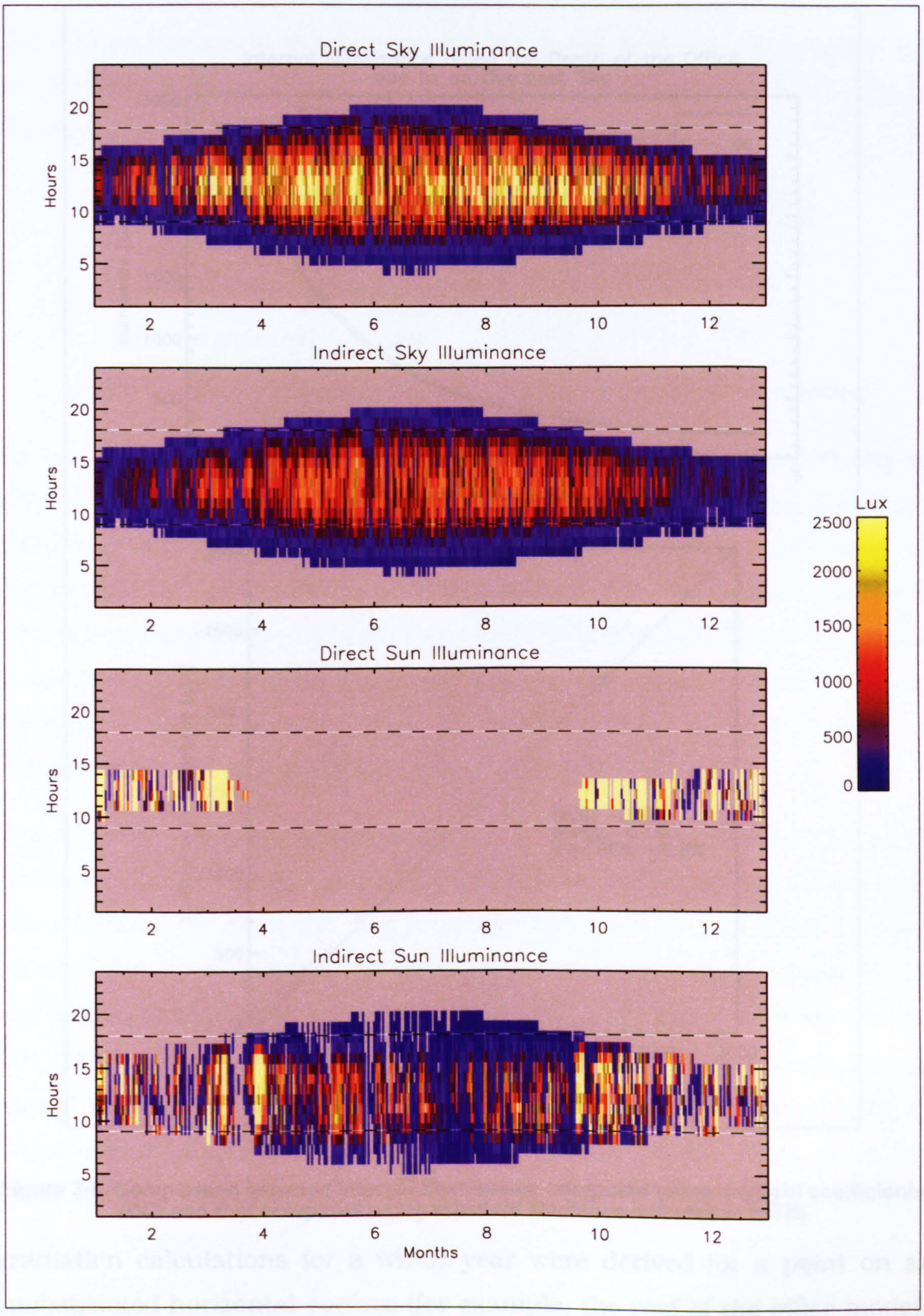

Figure 3-7 The four components of internal illuminance derived for a point on the workplane, 2.25m. from the window (facing due south)

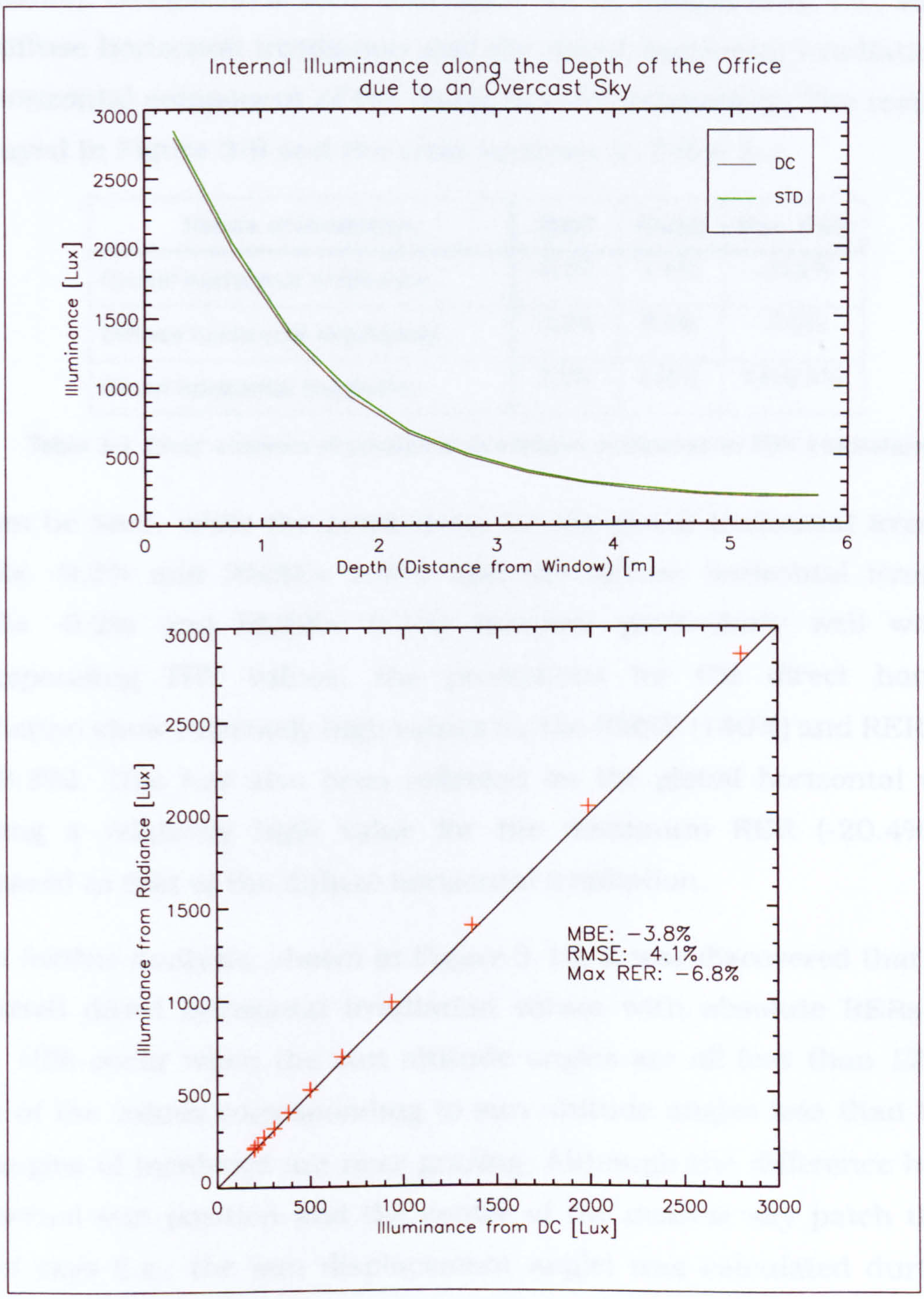

Figure 3-8 Comparison between internal illuminance computed using daylight coefficients (DC) and that computed using standard *Radiance* calculation (STD)

irradiation calculations for a whole year were derived for a point on an unobstructed horizontal surface (for example, the roof of the office model). These values were then compared with the irradiation values obtained from

TRY data for the same location. As well as comparing the values of global irradiation, comparisons were also made for its components, i.e., values of the diffuse horizontal irradiation and the direct horizontal irradiation (i.e., the horizontal component of the direct normal irradiation). The results are displayed in Figure 3-9 and the error analysis in Table 3-1.

Nature of Irradiation	MBE	RMSE	Max. RER
Global horizontal irradiation	-0.3%	1.4%	-20.4%
Diffuse horizontal irradiation	-0.2%	0.4%	-0.5%
Direct horizontal irradiation	2.3%	140%	7439.3%

Table 3-1 Error analysis of predicted irradiation compared to TRY irradiation

As can be seen, while the predictions for the global horizontal irradiation (MBE= -0.3% and RMSE= 1.4%) and the diffuse horizontal irradiation (MBE= -0.2% and RMSE= 0.4%) compare particularly well with the corresponding TRY values, the predictions for the direct horizontal irradiation show extremely high values for the RMSE (140%) and RER (max= 7,439.3%). This has also been reflected on the global horizontal values, causing a relatively high value for the maximum RER (-20.4%), i.e., compared to that of the diffuse horizontal irradiation.

Upon further analysis, shown in Figure 3-10, it was discovered that all the predicted direct horizontal irradiation values with absolute RERs larger than 10% occur when the sun altitude angles are all less than 12°, with most of the values corresponding to sun altitude angles less than 6°, i.e., the angles of incidence are near grazing. Although the difference between the actual sun position and the centre of the nearest sky patch through aimed rays (i.e., the sun displacement angle) was calculated during the validation of the XDAPS formulation to be only of the order of 1°, this displacement becomes relatively significant for very small sun altitude angles. For example, for a sun altitude angle of 2°, the magnitude of the error would correspond to $\frac{\sin 1°}{\sin 2°}$ = 0.5, i.e., a relative error of 50%.

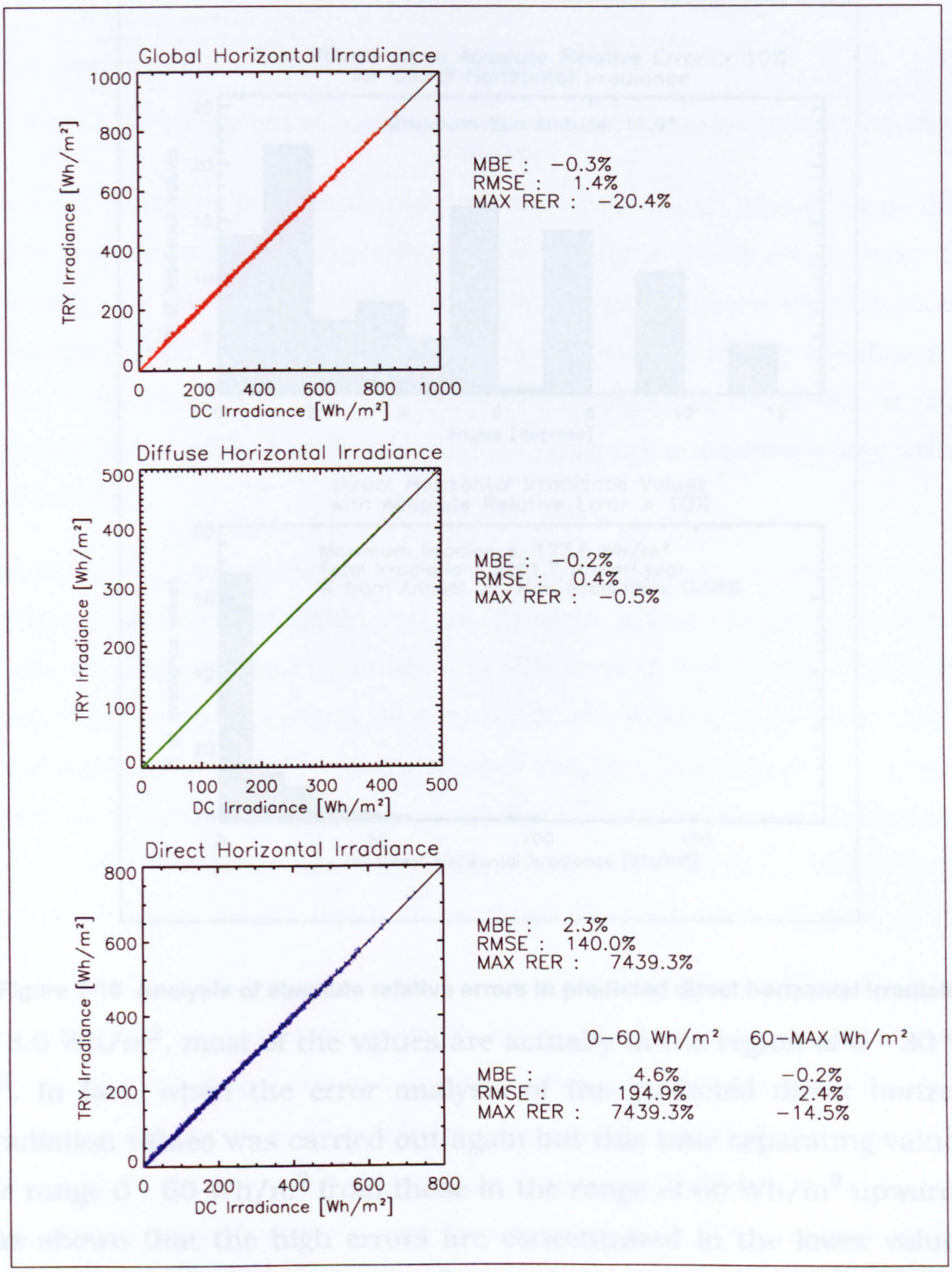

Figure 3-9 Comparison between irradiation computed using daylight coefficients (DC) and that from TRY data

However, looking at the frequency histogram of those same direct horizontal values with high errors, it can be seen that while their maximum value is

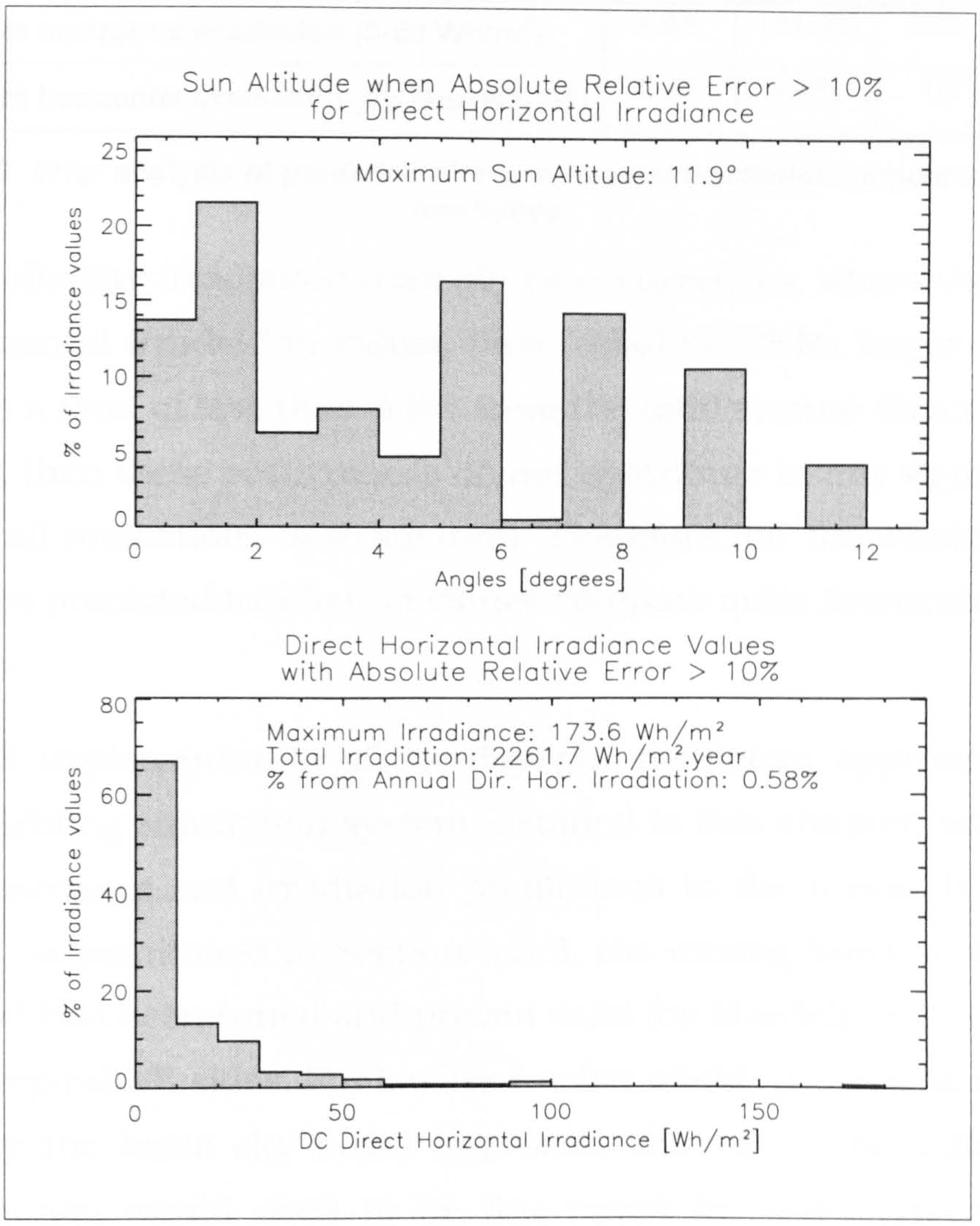

Figure 3-10 Analysis of absolute relative errors in predicted direct horizontal irradiation

173.6 Wh/m^2, most of the values are actually in the region of 0 - 30 Wh/m^2. In fact, when the error analysis of the predicted direct horizontal irradiation values was carried out again but this time separating values in the range 0 - 60 Wh/m^2 from those in the range of 60 Wh/m^2 upwards, it was shown that the high errors are concentrated in the lower values of irradiation, i.e., below 60 Wh/m^2. The higher irradiation values, on the other hand, show more accurate predictions with MBE= -0.2% and RMSE= 2.4%, Table 3-2.

Magnitude of Irradiation	MBE	RMSE	Max. RER
Direct horizontal irradiation (0-60 Wh/m^2)	4.6%	194.9%	7439.3%
Direct horizontal irradiation (60-Max Wh/m^2)	-0.2%	2.4%	10.1%

Table 3-2 Error analysis of predicted direct horizontal irradiation compared to TRY irradiation

Since the collective irradiation from all the occurrences, where the predicted direct horizontal irradiation values have absolute RERs larger than 10%, amounts to a total of less than 0.6% from the total annual direct horizontal irradiation, then these occurrences do not contribute in any significant way to the overall predictions of irradiation. Therefore, on the whole, it can be said that the predicted irradiation values compare quite favourably with the TRY values.

The XDAPS implementation of the daylight coefficient approach and the *Radiance* lighting simulation system, detailed in this chapter, was used for all the illuminance and irradiation predictions in the thesis. It should be noted that, as mentioned in Section 3.3.3, the mixing function for the sky blend model had been tuned and proven valid (by Mardaljevic) for Kew and, therefore, typical UK skies. For locales further afield, there is no compelling reason why the basic sky blend approach should not be valid, but the mixing function would need to be fine-tuned for skies typical of other climates.

In the following chapter, the methods typically used to assess the suitability of daylight for task functions inside buildings are reviewed. The hourly daylight illuminance values predicted using the XDAPS formulation are used to highlight some drawbacks related to the analysis approach of these methods, and some improvements are proposed. Then, a new daylight evaluation metric is introduced.

Chapter

4

New Metrics for Daylighting

"The sun was shining on the sea,
Shining with all his might:
He did his very best to make
The billows smooth and bright -
And this was odd, because it was
The middle of the night."

LEWIS CARROLL 1832-1898 (*THROUGH THE LOOKING-GLASS*, CH. 1)

As natural daylight is extremely dynamic and cannot be stored, the successful implementation of a daylighting concept/strategy requires careful assessment of the annual short-time-step profiles of internal daylight illuminances at an early design stage. Such internal illuminance profiles, which will mainly depend on the building design and the time-varying climatic boundary conditions, may serve as a basis for estimating the artificial lighting consumption in a building, modelling further interactions of the daylighting concept with, for example, the HVAC system, or predicting how the overall daylighting environment might be perceived by the occupants. It should be noted, however, that the latter point will depend on the occupants' designated tasks as well as their subjective and culturally-motivated preferences [Reinhart et al., 2001].

As discussed in Chapter 3, traditional daylighting metrics, principally DFs, are not considered adequate for a detailed investigation of the energy balance or the illuminance distribution in a daylit space since they exclude time-varying sky and sun conditions and ignore orientation effects. To this end, it seems appropriate to say that new daylighting metrics based on time-varying daylight illuminances are called for to address the following issues:

- The range of complexities associated with the assessment of daylight illuminance in non-domestic buildings, its impact on the electric energy consumed for lighting (and cooling), and its effective contribution to energy efficiency.
- The need to improve internal daylight illuminance appraisal methods in order to account for the recent developments in daylighting design techniques and innovative fenestration devices and identify where and how they can be applied effectively.
- The need to account for advanced lighting control technologies such as photoelectric control and continuous light dimming, and their incorporation into today's non-domestic buildings.
- The need to explore the opportunities created by techniques, such as the daylight coefficient approach, which uses realistic time-varying meteorological conditions to allow predictions that are more accurate than previously possible, in order to review the methods traditionally used to assess internal illuminance before these techniques were developed.
- The need to process the voluminous time-varying daylight illuminance data, obtained using the XDAPS formulation, such that it can be reduced to a simple meaningful quantity.
- The need to incorporate the effects of azimuth orientation in the daylight illuminance assessment process.

In this chapter, the time-varying daylight illuminances calculated in Chapter 3 are processed and evaluated using typically-used methods. Then, a new daylight evaluation metric is proposed, and it is applied on the base case office model.

4.1 Daylight Availability

As discussed earlier, illuminance levels at the workplane are typically used to evaluate the adequacy of illuminance for tasks carried out inside a space. It is necessary to ensure that the internal illuminance supplied contributes to satisfactory working conditions for the occupants since the minimum level of illuminance required depends on the purpose of the space. For example, a value of 100 - 200 lux is typically recommended in corridors, stairs, lobbies, and changing rooms, 300 - 500 lux in offices and classrooms for reading, writing, and computer use, and 1000 - 2000 lux for tasks involving minute detail, high precision, and low contrast, such as industrial assembly, manufacture, and testing [DETR, 1998b][DETR, 1999][CADDET-EE, 2001].

A measure of daylight availability is how many hours per year, when a workplace is occupied, a predefined minimum illuminance level is achieved/exceeded by daylight alone. This information can be drawn from the cumulative annual indoor illuminance distribution for a given point in a building and is sometimes referred to as 'daylight autonomy'. It should be noted that while the daylight autonomy is a uniquely defined physical quantity which describes the daylight availability at a point in a building, artificial lighting demand will also depend on the installed lighting system as well as occupancy patterns and individual preferences [Reinhart et al., 2000].

4.1.1 Cumulative Totals

The hourly internal illuminance data presented for one point in the office (in Figure 3-6) could be presented for all 12 calculation points (a separate plot for each point). Whilst instructive in revealing the patterns of daylight illuminance at a particular point, this presentation is clearly unhelpful for the assessment of illuminance performance. Further reduction of the data was thus needed to describe the availability of daylight illuminance in the entire office space in a single plot. A first step towards such reduction was to generate a two-dimensional histogram of cumulative totals for the whole office space as shown below.

Taking as input the hourly daylight illuminances derived in Section 3.3.3 with the office window facing due south, the numbers of hours in the working year[1] (between 09:00 and 18:00 hours), when certain 'threshold' values of daylight illuminance are exceeded, were computed for each of the 12 calculation points in the office model. Then, the numbers of hours were each multiplied by $\frac{100\%}{3650}$ in order to give percentages of the working year. The set of 21 threshold illuminance values whose availabilities were examined started with 0 lux, ended with 2000 lux, and incremented by 100 lux (i.e., 0 lux, 100 lux, 200 lux, 300 lux,.... until 2000 lux.) This way, the '4316 x 12' daylight illuminances were reduced to '21 x 12' values, which could be easily displayed in one plot.

By re-using the same daylight coefficients calculated in Chapter 3 and applying a rotation of 90° at a time to the generated luminances for the sun and sky patches (to account for different azimuths), a new set of hourly daylight illuminances was derived for the 12 points with the office facing due each of the main four azimuth orientations (i.e., '4316 x 12 x 4' values in total). The above testing for threshold illuminance levels was applied on each set of daylight illuminances, and the results are presented using false colours and contours in Figure 4-1.

Dotted lines in the figure mark threshold illuminances of 500 lux, 1000 lux, and 1500 lux (horizontal lines) and positions on the workplane 1 m., 3 m.,

1. There are 3,650 hours in the working year, of which 9.6% (350 hours) have zero daylight for this TRY. As mentioned earlier, this TRY has a total of 4,316 daylight hours.

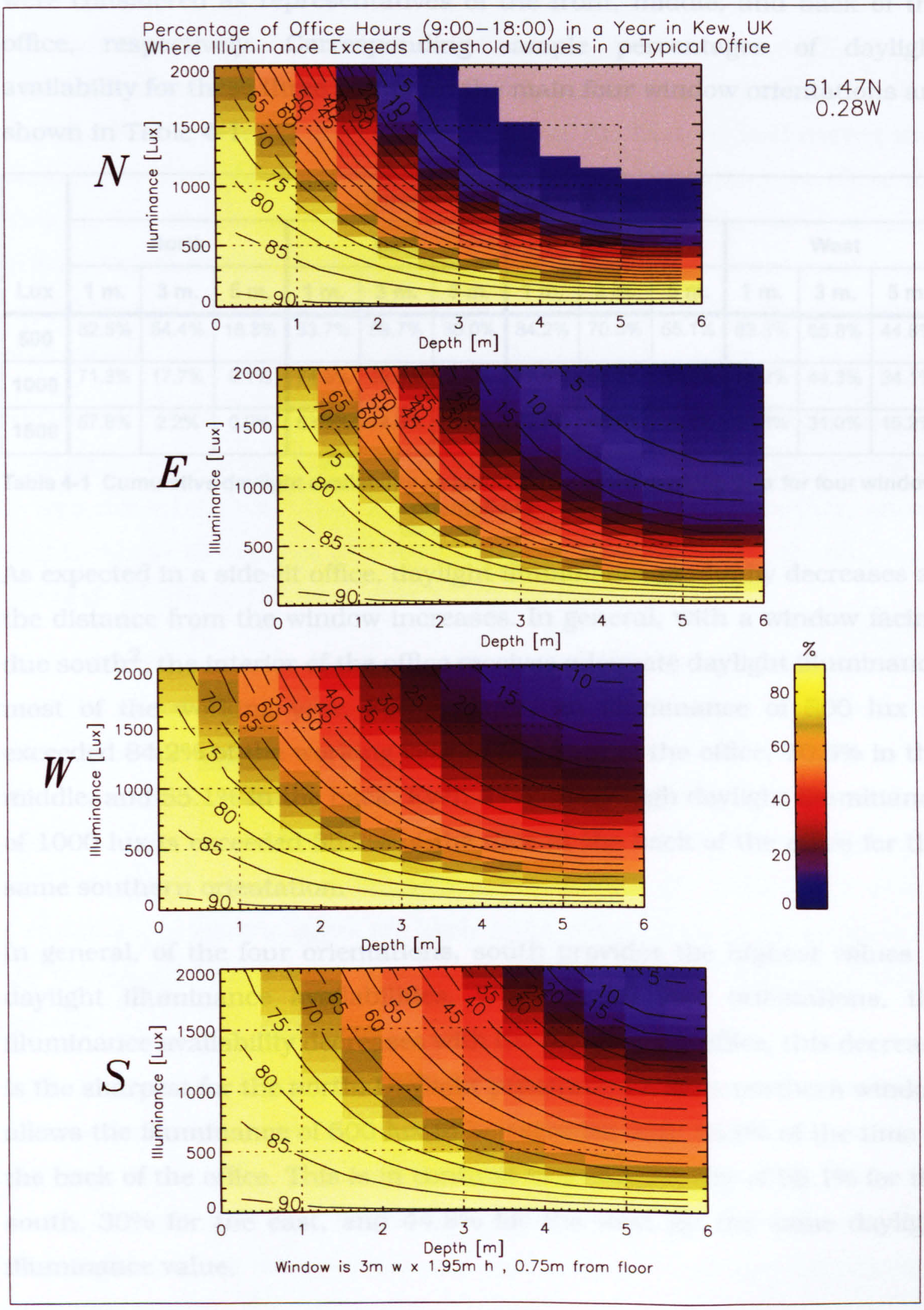

Figure 4-1 Cumulative illuminance availability for a line of 12 points on the workplane

and 5 m. from the window (vertical lines). These points on the workplane were considered as representatives of the front, middle, and back of the office, respectively. Corresponding sample percentages of daylight availability for these three points for the main four window orientations are shown in Table 4-1.

	Percentage of Working Year											
	North			East			South			West		
Lux	1 m.	3 m.	5 m.	1 m.	3 m.	5 m.	1 m.	3 m.	5 m.	1 m.	3 m.	5 m.
500	82.5%	54.4%	18.8%	83.7%	59.7%	30.0%	84.2%	70.5%	55.1%	83.3%	65.8%	44.8%
1000	71.3%	17.7%	0.1%	74.5%	29.5%	8.4%	77.9%	55.3%	35.7%	75.2%	44.3%	24.1%
1500	57.8%	2.2%	0.0%	63.3%	14.6%	2.4%	72.5%	45.1%	16.0%	67.6%	31.0%	15.2%

Table 4-1 Cumulative daylight availability as percentages of the working year for four window orientations

As expected in a side-lit office, daylight illuminance gradually decreases as the distance from the window increases. In general, with a window facing due south[2], the interior of the office receives adequate daylight illuminance most of the working year. For example, an illuminance of 500 lux is exceeded 84.2% of the working year in the front of the office, 70.5% in the middle, and 55.1% in the back. Even a relatively high daylight illuminance of 1000 lux is exceeded 35.7% of the time at the back of the office for the same southern orientation.

In general, of the four orientations, south provides the highest values of daylight illuminance availabilities. While in all four orientations, the illuminance availability decreases with the depth of the office, this decrease is the sharpest for the north. Daylight penetration from a northern window allows the illuminance of 500 lux to be exceeded only 18.8% of the time in the back of the office. This is in contrast to an availability of 55.1% for the south, 30% for the east, and 44.8% for the west for the same daylight illuminance value.

2. Note that the TRY is for Kew, UK, i.e., in the northern hemisphere.

Additionally, it was noted that the results associated with the western orientation in the middle and the back of the office are higher than those of the east since between 09:00 and 18:00 hours, there are more office hours in the afternoon than in the morning, i.e., the sun is in the western half of the sky hemisphere for more hours than in the eastern half during that period. For example, while 1000 lux is exceeded 44.3% and 24.1% of the time in the middle and back of the office, respectively, for a western orientation, the same daylight illuminance value at the same positions is available only 29.5% and 8.4% of the time, respectively, for an eastern orientation.

At the front of the office, there are generally small differences in illuminance availability among the four orientations for daylight illuminance values up to approximately 1000 lux. An illuminance of 1500 lux, however, shows slightly bigger differences with a 72.5% availability for the south, 63.3% for the east, 67.6% for the west, and 57.8% for the north.

In practical situations, however, not all daylight illuminances would be considered equally beneficial. Excessively high illuminances are associated with too much brightness and/or glare on the workplane and may cause discomfort to the office occupants. As a result, the occupants are likely to resort to operating some kind of blinds or shades on the window thus decreasing the amount of daylight admitted into the office as a whole. Consequently, electric lights are likely to be switched on to compensate for the shortage in illumination even though there is plenty of daylight available outside.

With cumulative totals, the calculation points in a space are treated independently of one another, i.e., the occurrences of the different levels of daylight illuminance are analyzed separately for each point. Since the source of daylight (i.e., the window) affects all the calculation points simultaneously, it would be more reasonable to analyze the daylight illuminance at all the points simultaneously and produce a 'quantity' that can describe daylight illuminance 'in a space' rather than just 'at a point'. This way, a more realistic description can be assembled of the internal illuminance profiles. The new metric introduced in Section 4.2 investigates a novel metric of daylight illuminance analysis that can address this issue.

4.1.2 Frequency Distribution

The cumulative totals plot showed how often a target illuminance value is achieved by daylight alone, but it is not possible to infer from these types of plots what the absolute values of daylight illuminance are. Frequency distribution is another data presentation format which is useful for displaying this information. A typical separate frequency histogram for each calculation point in the office, however, would not show how the daylight illuminance distribution varies along the depth of a space. A different plot was, therefore, developed which combines the frequency distribution data with the effect of the space depth. This is shown in Figure 4-2 for the office model with the window facing due south and in Figure 4-3 for different azimuth orientations.

The plot in Figure 4-2 was produced by distributing the predicted hourly daylight illuminances in a working year (for all 12 calculation points in the office) among 9 non-overlapping 'bins' of illuminance values covering a range from 0 lux (i.e., night-time) to 1000,000 lux as shown in the figure legend. The numbers of hours during which the daylight illuminances are within the limits of each of the bins were computed and then each multiplied by $\frac{100\%}{3650}$ in order to represent percentages of the working year. The results were then 'stacked' to form the plot in the figure. For example, daylight illuminances are in the range 300 - 500 lux for 2.8% of the time at the front of the office, 6.7% in the middle and 12.3% at the back. On the other hand, they are in the range 1000 - 2000 lux for 10.4%, 20%, and 30.3% of the time, respectively, for the same positions in the office, Table 4-2. Note that, as mentioned earlier, there is no daylight during 9.6% of the working year (for this UK climate file).

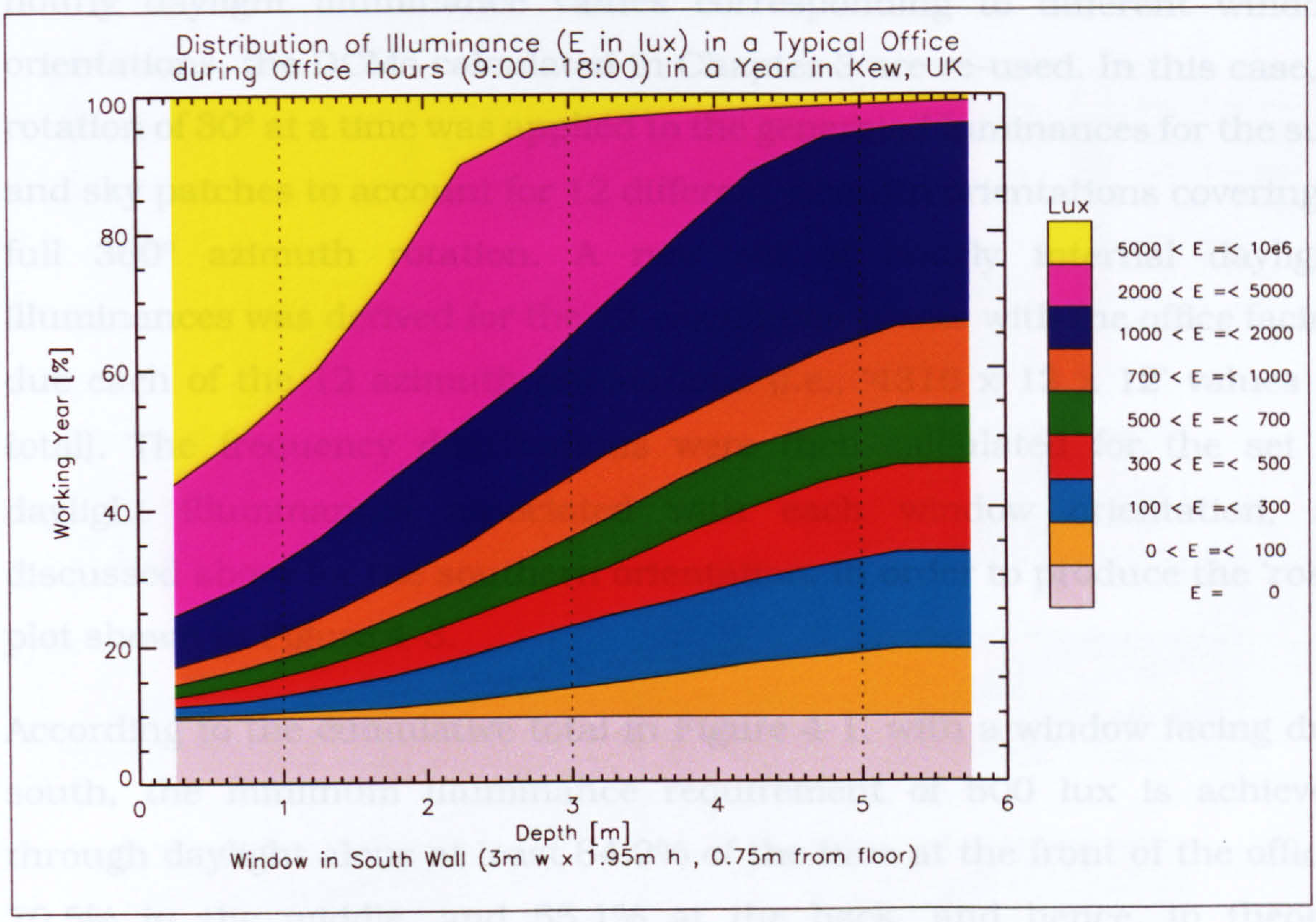

Figure 4-2 Stacked illuminance distribution with a window facing due south

	Percentage of Working Year		
Illuminance Bins (lux)	**1 m.**	**3 m.**	**5 m.**
E = 0	9.6%	9.6%	9.6%
0 < E ≤ 100	0.8%	4.2%	9.2%
100 < E ≤ 300	2.6%	9.0%	13.9%
300 < E ≤ 500	2.8%	6.7%	12.3%
500 < E ≤ 700	2.6%	6.4%	8.2%
700 < E ≤ 1000	3.6%	8.8%	11.2%
1000 < E ≤ 2000	10.4%	20.0%	30.3%
2000 < E ≤ 5000	23.1%	31.2%	4.0%
5000 < E ≤ 10^6	44.4%	4.2%	1.4%

Table 4-2 Illuminance distribution of 9 non-overlapping bins of illuminance values as percentages of the working year with a window facing due south

Similar to the process described in the previous section, in order to produce hourly daylight illuminance values corresponding to different window orientations, the DCMs calculated in Chapter 3 are re-used. In this case, a rotation of 30° at a time was applied to the generated luminances for the sun and sky patches to account for 12 different azimuth orientations covering a full 360° azimuth rotation. A new set of hourly internal daylight illuminances was derived for the 12 calculation points with the office facing due each of the 12 azimuth orientations (i.e., '4316 x 12 x 12' values in total). The frequency distributions were then calculated for the set of daylight illuminances associated with each window orientation, as discussed above for the southern orientation, in order to produce the 'rose' plot shown in Figure 4-3.

According to the cumulative total in Figure 4-1, with a window facing due south, the minimum illuminance requirement of 500 lux is achieved through daylight alone at least 84.2% of the time at the front of the office, 70.5% in the middle, and 55.1% at the back, and hence, in theory, considerable savings on artificial lighting use can be made. However, from the frequency distribution in Figure 4-2, it appears that while the daylight illuminance exceeds 2000 lux only 5.4% of the working year at the back of the office, this occurs 67.5% of the time at the front and 35.3% in the middle. These very high daylight illuminances can cause visual (and also thermal) discomfort to the occupants, rendering the results derived from the cumulative totals in Section 4.1.1, in effect, invalid in practice. In other words, knowing that 500 lux is achieved through daylight alone 84.2% of the time at the front of the office and 70.5% in the middle does not seem as promising when it is also known that during 67.5% and 35.3% of the time, respectively, the daylight illuminance is even higher than 2000 lux. Studies indicate that such level of daylight illuminance is considered too high for occupants' comfort [Roache, 2002]. Some kind of shading is almost certainly applied on the window in those cases, artificial lighting is switched

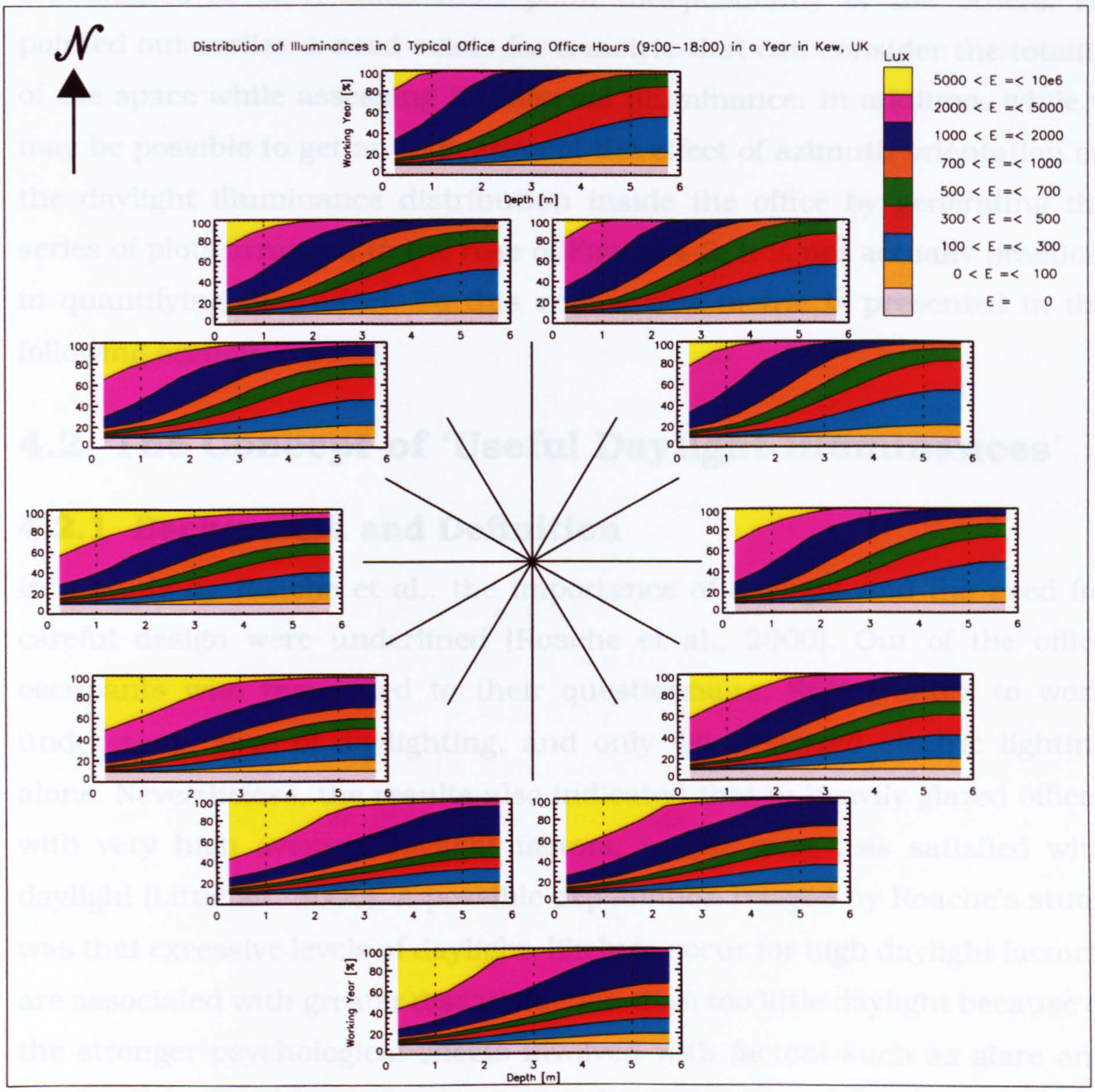

Figure 4-3 Effect of window orientation on the illuminance distribution with 6 mm. double glazing of transmittance 0.76

on instead, and the savings predicted on electric lighting would actually be non-attainable in practice[3].

3. Real world experiments indicate that the daylighting benefits of conventional glazings are not often fulfilled since they are usually associated with glare and inconsistent window management based on the use of manually (randomly) operated shades or blinds [Sullivan et al., 1994].

This again highlights the shortcoming of metrics that assess daylight illuminance at each calculation point independently of the others. As pointed out earlier, a need exists for a metric that can consider the totality of the space while assessing its internal illuminance. In addition, while it may be possible to get an indication of the effect of azimuth orientation on the daylight illuminance distribution inside the office by generating the series of plots arranged in the rose of Figure 4-3, it is not actually practical in quantifying that effect. To this end, a new metric is presented in the following section.

4.2 The Concept of 'Useful Daylight Illuminances'

4.2.1 Background and Definition

In a study by Roache et al., the importance of daylight and the need for careful design were underlined [Roache et al., 2000]. Out of the office occupants who responded to their questionnaire, 96% wanted to work under some form of daylighting, and only 4% preferred electric lighting alone. Nevertheless, the results also indicated that in heavily glazed offices with very high average daylight factors, people were less satisfied with daylight [Littlefair, 2000]. A possible explanation relayed by Roache's study was that excessive levels of daylight, likely to occur for high daylight factors, are associated with greater dissatisfaction than too little daylight because of the stronger psychological effects involved with factors such as glare and overheating. In addition, levels of daylight that are considered too low may easily be supplemented by electric lighting, whereas levels that are too high are associated with problems that are more complex to deal with (for example, thermal discomfort). It should be noted, however, that satisfaction with daylight is a complicated issue depending on many other factors such as facade orientation, obstructions, and the effectiveness of blinds [Roache et al., 2000].

While there are no conclusive studies available which correlate energy-efficient designs, dynamic envelope and lighting systems, occupant satisfaction with the environment, and worker productivity[4], there is currently a growing interest in the commercial building industry to provide both an energy-efficient and high quality work environment. Occupant surveys have uncovered some of the shortcomings of conventional design practice and have expanded the definition of an adequate office environment [Selkowitz et al., 1994]. In a study by Vine et al., all of the interviewees believed that it was important to have pleasant physical surroundings at work, and that it was difficult to work when they were physically uncomfortable [Vine et al., 1998]. Furthermore, there is growing evidence that workers appreciate offices that provide daylight and/or view or visual connections with the outdoors, and that such spaces have quantifiable effects on satisfaction and performance [Selkowitz, 1999]. Research has also shown that, in general, people prefer a space with a variation in the light pattern, and that where people have a slightly higher task illuminance than the general surround illuminance, their visual perception can be enhanced [CADDET-EE, 2000a]. It has also been noted that some variation of daylight levels is considered desirable as long as the limits are not significantly exceeded, and that the variability of natural light can have a stimulating effect and may even be essential for human biological functions[5] [Selkowitz et al., 1994].

Furthermore, researchers have noticed that lighting levels that are higher than the design workplane illuminance level are tolerated by the occupants unless there is glare or direct sun, in which case the occupants may select to shut the shading device [Lee et al., 1999]. Some studies also propose that occupants are more tolerant of glare from windows than that from electric

4. It has been demonstrated that light regulates some important metabolic activities in humans through a complex neuro-endronic system, whose external sensor is the eye [Rossi et al., 1995]. There is, also, anecdotal evidence that views of the outdoors, connections with the outside, a glare-free and thermally comfortable environment all contribute to a more satisfied worker, who is likely to be more productive [Selkowitz et al., 1994].

5. There is growing interest in providing relatively high light levels for short periods of time, particularly in northerly climates, for health-related reasons [Selkowitz et al., 1998].

lighting because the lighting source in the former case is accompanied by a view to the outside [Lee et al., 1998a].

Although direct sun can decrease the visibility of visual display terminal (VDT) tasks by reducing contrast or 'washing out' the screen image, the type of VDT can affect the magnitude of this problem. Older cathode-ray tube (CRT) screens are generally more susceptible to veiling reflections and direct sun washout. It is considered that newer display technologies, however, such as liquid-crystal display (LCD) screens with anti-reflection coatings, can be viewed under some direct sun conditions [Lee et al. 2000b]. Subjective observations made by Roache over several weeks during an experiment suggested that the visual environment when facing a computer workstation, which was at a right angle to the window, was reasonably comfortable when the working plane illuminance was below 1800 lux [Roache, 2002]. During that same experiment, it was noted that the daylight illuminance range of 700 - 1800 lux appeared to be acceptable for both computer and paper-oriented tasks.

In most of today's building applications, the desired total illuminance ranges from 150 lux to 1000 lux, with lower levels of ambient light considered acceptable if additional task illuminance[6] is provided [Reinhart et al., 2001][Selkowitz et al., 1998]. According to the Chartered Institution of Building Services Engineers (CIBSE) Code for Interior Lighting, an office should have a design illuminance level of 500 lux [Li et al., 2001]. However, during experiments carried out by Lawrence Berkeley National Laboratory (LBNL), when office workers were allowed to create their own lighting environment by manually controlling blade angles of mechanical Venetian blinds and varying the intensity of electric lighting, the resulting illuminances were on average 1493 ± 653 lux (840 - 2140 lux) in the morning and 1030 ± 248 lux (782 - 1278 lux) in the afternoon. This indicated that the occupants preferred higher light levels than those set by

6. It should be noted, however, that task lighting may defeat energy efficiency objectives but can satisfy occupants' requirements [Lee et al., 1999].

the automated control system (510 - 700 lux). In short, most of the occupants preferred greater illuminance levels from both daylight and electric lighting for their office space, even though they could see well enough to perform their tasks under the designer's recommended light levels [Vine et al., 1998]. The study by Roache et al. on office workers' views on daylight and lighting also suggested that the amount of time that respondents spent working by daylight alone was maximized for some higher level of average daylight factor (ADF), estimated at 8% (i.e., 800 lux) [Roache et al., 2000].

That said, it should be noted that the spatial distribution of daylight within the room can influence the occupant's perception of illuminance at the workplane. It was found that even with the provision of adequate daylight at the workplane, occupants wanted more light (on the order of 800 - 1400 lux) perhaps to compensate for the darker luminance levels in the back of the room characteristic in a side-lit space. Other studies have shown that occupants with a relatively glare-free environment are satisfied with lower workplane illuminance levels than the design level [Lee et al., 1999]. It should be also noted that lighting requirements are essentially subjective. There is a large range of lighting conditions over which the human eye performs satisfactorily, and there is equally a large range of variation among individuals as to what comprises satisfactory conditions [BRE, 1987].

Moreover, it has been argued that direct sun with controlled intensity can be pleasant in a work space on a winter day [Lee et al., 2000a]. A survey (conducted by the BRE) of office workers suggested that 73% of them considered sunlight a pleasure rather than a nuisance [Littlefair, 1991]. That said, the requirement for sunlight will vary according to the type of non-domestic building and the extent to which the occupants can control their environment. It is believed that people better appreciate it if they have control/choice over their exposure to sunlight, for example, by using adjustable shading devices or by changing their positions in the room [Littlefair, 1991].

Hence, in view of all the previous points, the daylight illuminance range of 100 - 2000 lux has been chosen in this study, in the first instance, as a target range to symbolise 'useful and desired daylight illuminance levels in an office environment' since it can be deduced that:

- Daylight illuminances less than 100 lux are insufficient to be either the sole source of illumination or to contribute significantly to artificial lighting.
- Daylight illuminances in the range 100 - 500 lux are considered useful and convenient (with perhaps localised task illuminance provided).
- Daylight illuminances in the range 500 - 2000 lux are desirable and tolerated.
- With daylight illuminances higher than 2000 lux, discomfort is likely to occur.

This concept of 'useful daylight illuminances' allows the simultaneous quantification of internal illuminance at calculation points along the depth of a side-lit space, rather than analyzing each point separately, i.e., it can describe daylight illuminance 'in a space' rather than just 'at a point' (as shown in the following section). Also, by definition, it provides an indication of illumination uniformity in the space since the daylight illuminances will need to be in the range of 100 - 2000 lux in order to be considered 'useful'. Note that this uniformity range is necessarily much wider than that traditionally considered acceptable for daylight factors[7] [Dewey et al., 1998].

In terms of simplicity, useful daylight illuminances are comparable with daylight factors, i.e., a single number which characterises daylight illuminance performance and which can be easily understood by architects and designers. In contrast to DFs, however, it is based on realistic time-

7. The CIBSE Code for interior lighting recommends that the uniformity of illuminance (minimum to average illuminance) over any task area and immediate surround should not be less than 0.8 [Dewey et al., 1998]. This ratio is 0.1 in this case.

varying sky and sun conditions, and so it is likely to better describe the true daylighting performance of a space.

It should be mentioned at this point that further occupant-based studies are needed to investigate how daylight illuminance distribution, lighting quality, and room design affect occupants' preferences of workplane illuminance under real sky and sun conditions. Results from these future studies could be used to refine/change the criteria for useful daylight illuminance.

4.2.2 Application

Many building facades feature tinted glazings to reduce solar gain and possibly glare. These tinted glazings can have a major impact on the potential for daylight illumination. Hence, in addition to clear double glazing, the useful daylight illuminances associated with glazings of typical medium (antisun green) and heavy (antisun bronze) tints are predicted in this section. Also, as outlined in the schematic of Figure 4-4, the electric

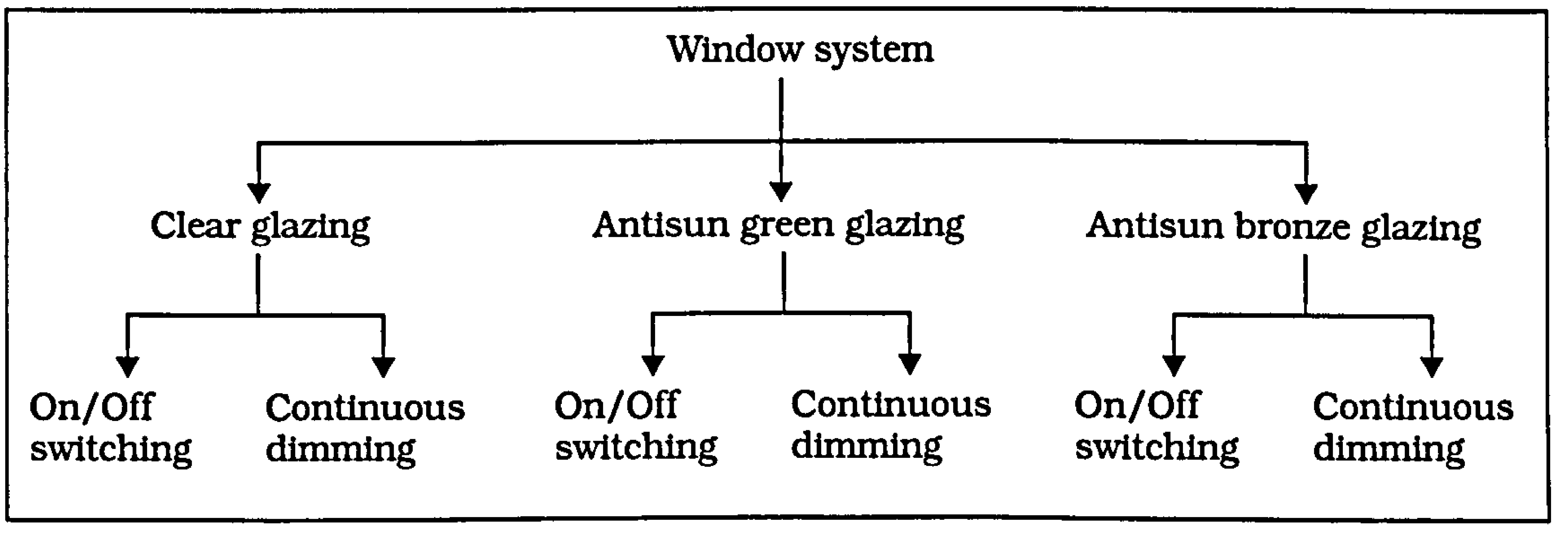

Figure 4-4 Schematic of window elements and associated electric lighting controls

energy consumed by two types of lighting control scenarios (manual on/off switching and automatic continuous dimming) operated in response to daylight illuminance in an office with the clear and tinted glazings are calculated later in Section 4.3.

In applying the concept of useful daylight illuminances on the office model, initially presented in Section 3.3.1, the 2 points closest to the window and the 2 points closest to the back wall are not included. Only the points in the 'core length of the office' are considered, i.e., the 8 points at workplane level starting at 1.25 m. and ending at 4.75 m. from the window, as shown in Figure 4-5. This 'central part' of the office or the 'core length of the office' is

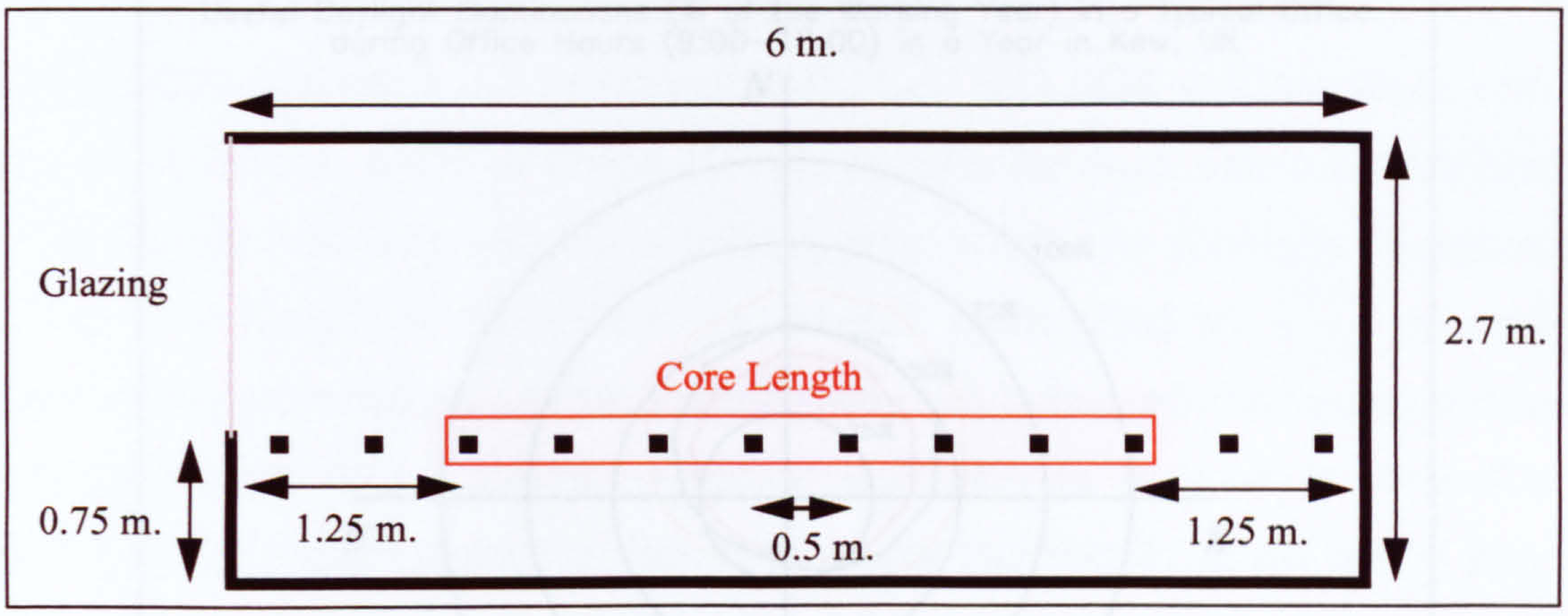

Figure 4-5 Core length of the office model

usually where most of the activity takes place and where most tasks are carried out by the occupants. The area closest to the window and that closest to the back wall, on the other hand, are typically associated with the extremes at both ends of the range of daylight illuminance values in a side-lit space, i.e., 'too much' and 'too little' daylight illuminance, respectively, and therefore not usually favoured by occupants. As such, it has been considered reasonable to exclude these areas of extreme daylight illuminances when applying the concept of useful daylight illuminances.

Hence, at any instance (hour in the working year), the daylight illuminance in the office will be considered 'useful' only if the daylight illuminance values at all the points in the core length are larger than 100 lux and less than or equal to 2000 lux., i.e., 100 lux < (illuminances in the range of 1.25 m.- 4.75 m. from the window) ≤ 2000 lux

In a UK office with an unshaded clear double-glazed south-facing window, as in Figure 4-2, the daylight illuminances in the core length of the office fall in 'the useful range' only 17.6% of the working year (643 out of 3650 hours). The polar plot in Figure 4-6 shows the percentages of the working year when

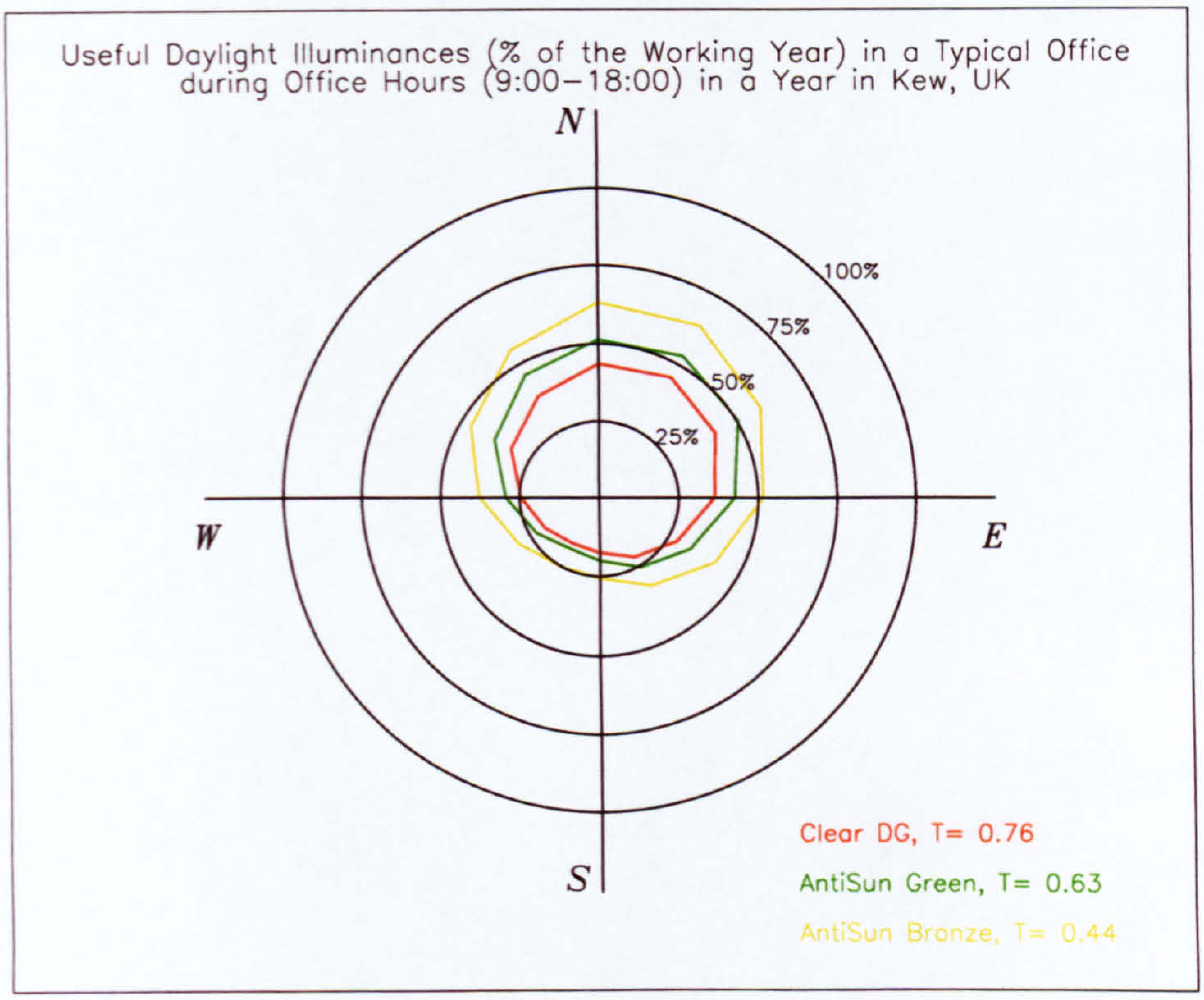

Figure 4-6 Effect of orientation and type of glazing on occurrence of useful daylight illuminances

the core length of the office receives useful daylight illuminances calculated for 12 window orientations starting from north and incrementing by 30° at a time in order to cover a complete 360° azimuth rotation. It transpires that in contrast to 17.6% of the working year with a south-facing window, the office receives useful daylight illuminances 36.3%, 43.6%, and 24.6% with an east-, north-, and west-facing window, respectively. The effect of the type of glazing, i.e., different values of transmittance, was also investigated and plotted in the figure, and the results are summarized in Table 4-3.

Type of Double Glazing	Percentage of Working Year			
	North	East	South	West
Clear (T=0.76)	43.6%	36.3%	17.6%	24.6%
Antisun green (T=0.63)	51.4%	42.7%	20.2%	29.3%
Antisun bronze (T=0.44)	63.1%	51.6%	25.6%	37.7%

Table 4-3 Occurrences of useful daylight illuminances with different orientations and different types of glazing

Note that in the polar plot in Figure 4-6, '4316 (daylight hours) x 12 (calculation points) x 12 (orientations)', i.e., 621,504 values, were reduced to just 12 values. Each of these 12 values (one for each azimuth orientation) is the number of hours in the working year when the daylight illuminances in the core length of the office are 'useful' multiplied by $\frac{100\%}{3650}$ in order to represent a percentage of the working year. In other words, using the useful daylight illuminance metric, a single quantity is utilized to describe the daylight illumination and uniformity along the depth of an office space of virtually any azimuth orientation based on real time-varying sky and sun conditions.

The fact that there are more useful daylight illuminances in an office facing due north than one facing due south can be explained using Figure 4-3, which shows that with a southern orientation, daylight illuminances higher than 2000 lux (i.e., outside the useful range), probably due to direct sunlight, occur much more often than with a northern orientation[8]. The same logic can be applied to explain why using double glazing of lower transmittance, for example antisun green (transmittance 0.63) or antisun bronze (transmittance 0.44) [Pilkington, 1991], produces more occurrences of useful daylight illuminances than clear glazing (transmittance 0.76). Since a lower glazing transmittance results in lower daylight illuminances inside the office, then during more hours in the working year, daylight

8. For a location in the northern hemisphere such as Kew, UK.

illuminances in the core length of the office will more likely fall under 2000 lux and into the useful range.

4.2.2.1 Visualization of Annual Daylight Illuminance Profiles

In addition to knowing the frequency of occurrences of useful daylight illuminances as a percentage of the working year, it is instructive, especially for architects and designers, to also 'visualize' when these useful daylight illuminances actually occur, i.e., the daily and seasonal patterns in the occurrence of useful daylight illuminances. Hence, a data analysis routine was developed in order to produce the '365 x 24' matrices in Figure 4-7, where a whole year of daylight illuminances in the core length of an office with clear double gazing is formatted as follows:

- All hours where the daylight illuminances at all the core points are in the useful range are represented by a green colour.
- All hours where one or more points have daylight illuminances higher than 2000 lux are represented by a blue colour (i.e., above useful range).
- All hours where one or more points have daylight illuminances equal to or lower than 100 lux are represented by a red colour (i.e., below useful range).
- All darkness hours (i.e., of zero daylight illuminance) are represented by a grey colour.

The two horizontal dashed lines in each matrix plot denote the start and finish hours of a typical working day, for example, 09:00 and 18:00 hours. This analysis was carried out for the main four azimuth orientations of the office window.

Note that there are no occurrences of hours (as confirmed by a flag test) where one or more points in the core length of the office have daylight illuminances lower than 100 lux while at the same time one or more points have daylight illuminances higher than 2000 lux. This is possibly related to

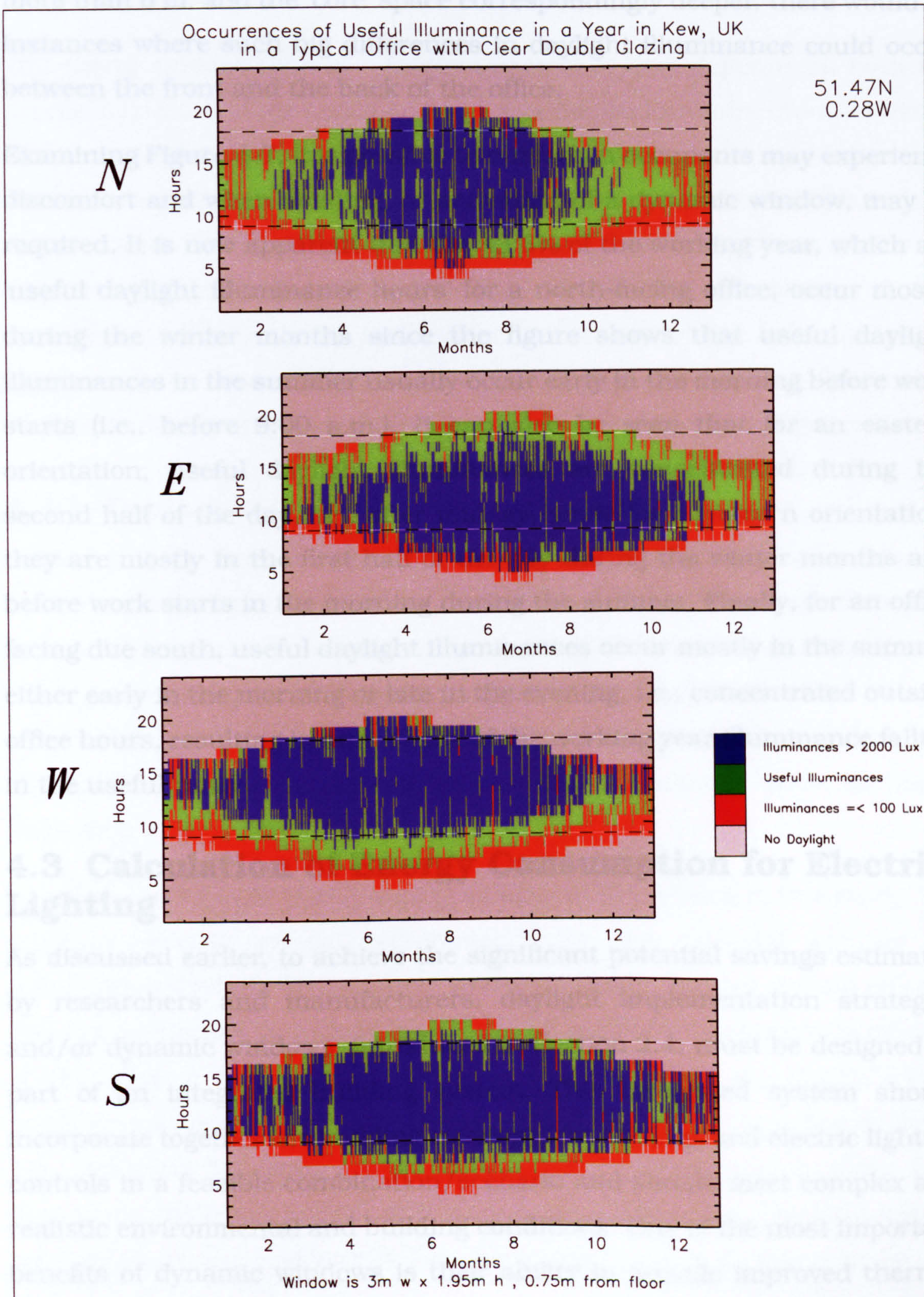

Figure 4-7 Useful daylight illuminances annual profiles

the dimensions of the office model. Perhaps if the depth of the office were more than 6 m. and the 'core' space correspondingly deeper, there would be instances where such big differences in daylight illuminance could occur between the front and the back of the office.

Examining Figure 4-7, it is possible to note when occupants may experience discomfort and when shading, or activation of a dynamic window, may be required. It is now apparent that the 43.6% of the working year, which are 'useful daylight illuminance hours' for a north-facing office, occur mostly during the winter months since the figure shows that useful daylight illuminances in the summer usually occur early in the morning before work starts (i.e., before 9:00 a.m.). It can also be seen that for an eastern orientation, useful daylight illuminances are concentrated during the second half of the day, i.e., after midday, while for a western orientation, they are mostly in the first half of the day during the winter months and before work starts in the morning during the summer. Finally, for an office facing due south, useful daylight illuminances occur mostly in the summer either early in the morning or late in the evening, i.e., concentrated outside office hours, resulting in only 17.6% of the working year illuminance falling in the useful range.

4.3 Calculation of Energy Consumption for Electric Lighting

As discussed earlier, to achieve the significant potential savings estimated by researchers and manufacturers, daylight implementation strategies and/or dynamic windows, introduced in Section 2.4, must be designed as part of an integrated building system. This integrated system should incorporate together the building envelope, daylighting, and electric lighting controls in a feasible combination/scenario and should meet complex and realistic environmental and building conditions. One of the most important benefits of dynamic windows is their ability to provide improved thermal and visual comfort, and other amenities such as privacy. In this study, the analysis is mainly concerned with daylight provision issues, energy demand related to artificial lighting requirements, and energy production in the case of photovoltaics.

The energy consumption of a lighting control system depends on both the precise operation of the control system and the performance characteristics of the particular lamps and ballast. However, to a very good approximation, the on-time of the luminaires and the total amount of extra light (i.e., which complements daylight) delivered to the workplane (in lux-hours) depend only on the control system [Roache, 2002]. The advantage of this approximation is that the performance/efficiency of the lighting control system may be assessed in relation to workplane illuminance levels. The performance of two types of lighting controls are discussed below.

4.3.1 Daylight-Linked On/Off Light Switching

As discussed in Section 2.2.1, the efficacy of fluorescent lighting depends upon the lamp/luminaire/ballast combination. The 'net system efficacy' of electric lighting can be estimated by dividing the maintained illuminance levels (at the workplane) by the lighting power density[9]. While a very energy-efficient electric lighting system might have an efficacy as high as 50 lm/W (500 lux ÷ 10 W/m^2), a more typical efficacy value is 20 - 30 lm/W [Selkowitz et al., 1998].

In order to assess the energy saving benefits of daylighting in this study, the auxiliary electric energy requirements for the artificial lighting (to complement daylight illuminance) were calculated. The net system efficacy was first computed as follows. A value of 80 lm/W for the luminous efficacy of the electric lamps was considered [Vartiainen et al., 2000]. Three luminaires were assumed to be attached to the ceiling of the office model at 1m., 3m., and 5m. from the window, respectively, in order to cover (i.e., illuminate) the front, middle, and back zones of the office. The light output ratio (LOR) of the luminaires (i.e., their efficiency) was taken to be 0.5

9. The lighting power density is defined as the lighting power in watts per unit area of a building in m^2.

[DETR, 1999]. Each of the luminaires was considered to be controlled independently[10] according to the lighting requirement and the daylight illuminance of the office zone it illuminated. In addition, assuming a light loss factor of ~10% due to dirt and ageing depreciation, the average net luminous efficacy of the electric lighting system at workplane level was taken to be 36 lm/W [Vartiainen, 2001], i.e.,

$$80 \text{ lm/W} \times 0.5 \times 0.9 = 36 \text{ lm/W}$$

The lighting power density in this case was 13.89 W/m^2 (500 lux ÷ 36 lm/W).

To simulate manual on/off switching of the luminaires, the electric lighting with an output constant at 500 lux was modelled to be switched on at any hour when this level of illuminance was not supplied by daylight alone. That is, at any hour when daylight illuminance falls below 500 lux, the electric lighting was assumed to be fully on, and otherwise, fully off. It should be noted that this is an ideal version of manual on/off switching since in real-life applications, it cannot be guaranteed that the operation of lights would be perfectly daylight-linked, and that occupants would always switch off artificial lights when daylight is sufficient. In fact, studies show that once turned on, electric lighting is rarely turned off, regardless of changes in task or daylighting conditions. It is assumed that this is due to both the location of the switch, usually near the door, as well as visual adaptation of the occupants' eyes [Sweitzer, 1991].

Since in the case of an on/off light switching system, whenever the luminaires are switched on, they are fully on and otherwise fully off, then the amount of total illumination that is provided per working year by each of the three luminaires can be obtained by counting the number of hours in

10. An Information Paper from the Building Research Establishment (BRE) revealed that one of the ways to minimize the risk of occupants' dissatisfaction with lighting control systems was for each luminaire to have its own integral controls (Information Paper 'People and Lighting Controls', IP 6/96, Slater, I. A., Bordass, W., T., and Heasman, T. A., Garston: CRC, July 1996) [Knight, 1999].

the year when daylight illuminance under each luminaire falls below 500 lux and multiplying it by 500 lux. For example, in a UK south-facing office, the total illumination produced by the luminaires could be calculated as:

- 288.3 klux-hour for the front.
- 539 klux-hour for the middle.
- 819.3 klux-hour for the back.

Dividing these illumination values[11] by 36 lm/W, which is the net luminous efficacy of the on/off electric lighting system at workplane level as per the above discussion, the annual electric energy required by the three luminaires was estimated to be:

- 8 kWh/m^2.year to be consumed by the front luminaire.
- 15 kWh/m^2.year to be consumed by the middle luminaire.
- 22.8 kWh/m^2.year to be consumed by the back luminaire.

Hence, the total annual electric energy requirement for the office's artificial lighting due to a manual on/off switching operation was estimated to be $\frac{8+15+22.8}{3\text{ zones}} = 15.2$ kWh/m^2.year.

Similar calculations were carried out for 12 different azimuth orientations for the office window starting from north and incrementing by 30° at a time in order to cover a complete 360° azimuth rotation. The electric energy consumed by all three luminaires during all the hours in the working year was used to produce an annual total for the office for each of the 12 azimuth orientations. In addition to clear double glazing, the total energy consumption was calculated when the window had two darker tints, antisun green and antisun bronze, as shown in the polar plot of Figure 4-8.

Note that the electric lighting energy demand is inversely proportional to the glazing transmittance, i.e., it is highest in an office with a window of antisun

11. Note that lux = lm/m^2.

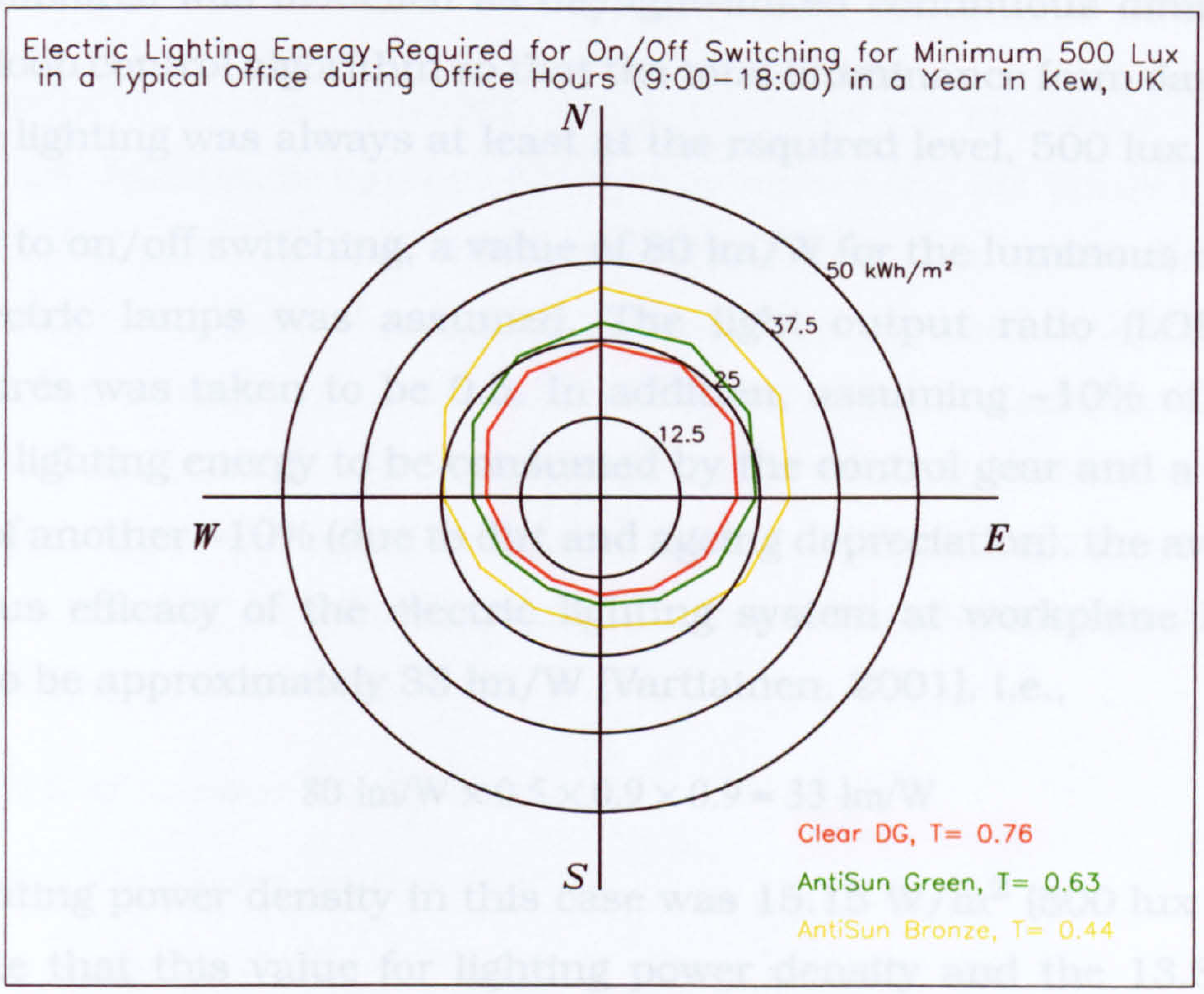

Figure 4-8 Effect of orientation and type of glazing on annual lighting energy demand with on/off switching control

bronze glazing and lowest for an office with clear double glazing. In addition, for all 3 tints of glazing, an office with a window facing due south consumes the least amount of electric energy for lighting followed by west then east and north with the highest consumption. For example, with clear double glazing, the annual electric lighting consumption is 15.2, 17.9, 21.4, and 24.4 kWh/m^2 for south, west, east, and north, respectively.

4.3.2 Daylight-Linked Continuous Light Dimming

In daylight-linked continuous dimming of artificial lighting, the luminaires are controlled in such a way that they complement daylighting by 'topping-up' the illuminance to the required level, whenever it is not attained using daylight alone, and are dimmed down whenever daylight illuminance is sufficient. Again, each of the three luminaires was considered to be controlled independently according to the lighting requirement and the daylight illuminance of the office zone it illuminated. The lighting control of the luminaires was modelled as daylight-linked continuous dimming in a closed loop control algorithm so that the total illuminance from daylight and electric lighting was always at least at the required level, 500 lux.

Similar to on/off switching, a value of 80 lm/W for the luminous efficacy of the electric lamps was assumed. The light output ratio (LOR) of the luminaires was taken to be 0.5. In addition, assuming ~10% of the total electric lighting energy to be consumed by the control gear and a light loss factor of another ~10% (due to dirt and ageing depreciation), the average net luminous efficacy of the electric lighting system at workplane level was taken to be approximately 33 lm/W [Vartiainen, 2001], i.e.,

$$80\ \text{lm/W} \times 0.5 \times 0.9 \times 0.9 \approx 33\ \text{lm/W}$$

The lighting power density in this case was 15.15 W/m^2 (500 lux ÷ 33 lm/W). Note that this value for lighting power density and the 13.89 W/m^2 assumed for on/off light switching in the previous section were reasonably efficient values[12], considering that typical office lighting power density values sited in the literature (empirical, installed, and modelled) varied as follows:

- 10 W/m^2 [Selkowitz et al., 1998][Reinhart et al., 2001].
- 13 W/m^2 [Vine et al., 1998].
- 14.53 W/m^2 [Lee et al., 1999][Lee et al., 2000a].
- 15 W/m^2 [Vartiainen et al., 2000].
- 16.1 W/m^2 [Sullivan et al., 1996a].
- 20 W/m^2 [Lam et al., 1999].

12. The 1994 CIBSE Code for Interior LIghting regards a commercial fluorescent lighting system as achieving energy efficiency good practice if it uses between 2.2 and 5.4 W/m^2 per 100 lux [Knight, 1999].

- 22 W/m^2 was also reported as a widely accepted upper limit for lighting power demand[13] [Love, 1995].

The amount of total illumination that is provided per working year by each of the three luminaires can be obtained by identifying the hours in the year where daylight illuminance under each luminaire falls below 500 lux and calculating the deficit/shortage in illumination required to bring it up to 500 lux. For example, in a UK south-facing office, the total illumination (in lux-hours) that needs to be provided per working year by the three luminaires along the office to top up the internal illuminance to 500 lux (whenever needed) in a daylight-linked continuous dimming operation was calculated as:

- 225.8 klux-hour for the front.
- 368.9 klux-hour for the middle.
- 524.8 klux-hour for the back.

Dividing these illumination values by 33 lm/W, which is the net luminous efficacy of the electric lighting system at workplane level as per the above discussion, the electric energy required annually by the three luminaires was estimated to be:

- 6.8 kWh/m^2.year to be consumed by the front luminaire.
- 11.2 kWh/m^2.year to be consumed by the middle luminaire.
- 15.9 kWh/m^2.year to be consumed by the back luminaire.

The total annual energy requirement for the office's artificial lighting is thus predicted to be $\frac{6.8 + 11.2 + 15.9}{3 \text{ zones}} = 11.3$ kWh/m^2.year. This is 26% less energy than that required by the manual on/off light switching system (15.2 kWh/m^2.year) modelled in Section 4.3.1 for the same office, location, and climate.

13. For example, many older systems in existing buildings in the U.S. require 21.5 - 32.3 W/m^2 [Johnson, 1995]. On the other hand, new high-performance artificial lighting systems can have an installed power density of 8 W/m^2 [Bodart et al., 2002].

It is important to note that it is not suggested here that this exact energy consumption figure be taken as a general recommendation for office installations since this depends on the precise meteorological conditions at the location. Rather, it serves as a 'base case' value to make comparisons against in later sections.

Similar energy calculations were carried out for 12 different azimuth orientations for the office window starting from north and incrementing by 30° at a time in order to cover a complete 360° azimuth rotation. The electric energy consumed by all three luminaires during all the hours in the working year was used to produce an annual total for the office for each of the 12 azimuth orientations. In addition to clear double glazing, the total energy consumption to top up (complement) the internal illuminance to 500 lux was calculated when the window had two darker tints, antisun green and antisun bronze, as shown in the polar plot of Figure 4-9.

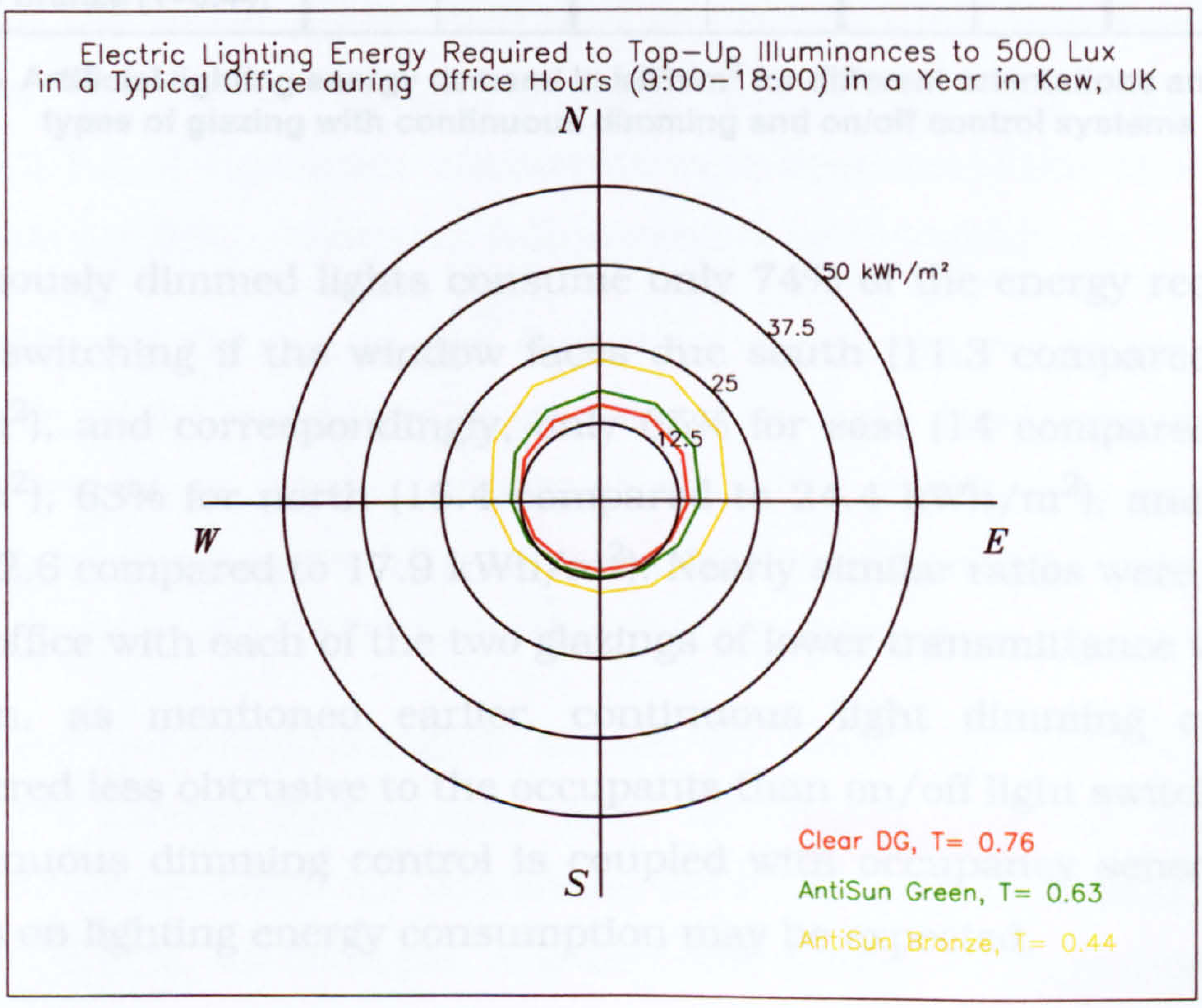

Figure 4-9 Effect of orientation and type of glazing on annual lighting energy demand with continuous dimming control

As noted with manual on/off light switching, the figure shows that the lower the transmittance of the glazing, the higher the lighting energy demand will be. Also, for all 3 tints of glazing, an office with a window facing due south consumes the least amount of electric energy for lighting followed by west then east and north with the highest consumption. For example, with clear double glazing, the annual electric lighting consumption is 11.3, 12.6, 14, and 15.4 kWh/m^2 for south, west, east, and north, respectively. As can be expected, however, with a manual on/off switching system, the electric energy demand for lighting is much higher than for automatic continuous dimming, Table 4-4. For example, for an office with clear double glazing,

	kWh/m^2							
	North		East		South		West	
Type of Double Glazing	Dim	On/Off	Dim	On/Off	Dim	On/Off	Dim	On/Off
Clear (T=0.76)	15.4	24.4	14.0	21.4	11.3	15.2	12.6	17.9
Antisun green (T=0.63)	17.7	28.0	15.9	24.4	12.4	16.8	14.0	20.1
Antisun bronze (T=0.44)	22.6	33.6	20.0	29.7	14.8	20.3	17.2	24.7

Table 4-4 Artificial lighting energy demand in kWh/m^2 for different orientations and different types of glazing with continuous dimming and on/off control systems

continuously dimmed lights consume only 74% of the energy required by on/off switching if the window faces due south (11.3 compared to 15.2 kWh/m^2), and correspondingly, only 65% for east (14 compared to 21.4 kWh/m^2), 63% for north (15.4 compared to 24.4 kWh/m^2), and 70% for west (12.6 compared to 17.9 kWh/m^2). Nearly similar ratios were observed for an office with each of the two glazings of lower transmittance values. In addition, as mentioned earlier, continuous light dimming control is considered less obtrusive to the occupants than on/off light switching, and if continuous dimming control is coupled with occupancy sensors, more savings on lighting energy consumption may be expected.

It should to be noted at this point that the realistic control of light dimming and dynamic window systems is likely to be more accurately simulated using small time-steps, for example 5 minutes. This is because meteorological data shows significant variations on short-time scales and hence would have an impact on responsive window devices and lighting controls. Since high resolution weather data is currently not readily available, this study could only use the commonly available hourly climate files. It should be also noted that by using the XDAPS formulation, modelling the impact of short time-step weather data would not be a computational problem. As detailed in Section 3.1.2, only the calculation of the daylight coefficient matrices is computationally expensive due to the inter-reflection calculation, but this is carried out only once to produce a set of daylight coefficients for a proposed design. Deriving illuminances from DCMs, on the other hand, is computationally cheap since it involves simple algebra, and so increasing the number of individual sky luminance distributions from hourly to, for example, half hourly or quarter hourly, would add little to the computation time needed for studying a whole year. Hence, the same values of daylight coefficients already calculated earlier in the study can be simply re-used with any smaller time-step weather data, provided the office design remains unchanged. As discussed in Section 3.1.2, if significant alterations were introduced into the design of the office, daylight coefficients would need to be re-calculated.

It is worth mentioning as well that there have been recent reports on a stochastic model which can synthesize short-term irradiance time series from hourly mean values, initially developed by Skartveit et al. and then modified, adapted, and validated for daylight simulations by Walkenhorst et al., [Skartveit et al., 1992][Walkenhorst et al., 2002].

The above notwithstanding, it should be noted that although a very responsive window system may meet all control objectives adequately, especially under transient conditions (such as passing clouds), frequent blind movement, for example, may be unacceptable to users (noise, visual distraction) and may also result in shortened product life [Vine et al., 1998]. The same applies to an automatic on/off light switching where excessive luminaire switching may be disturbing to occupants. Thus, careful consideration needs to be given to the design of such control systems (for example, considering the introduction of delay times in system response).

4.4 Glare Subjective Rating

While it was not planned to dedicate a sizable part of this study to glare metrics, it was decided to address one aspect of visual comfort in the form of glare subjective rating. As such, an indication of the visual environment in an office with clear double glazing can be obtained and used as a base case for comparison with the impact of switchable window devices in the next chapter.

4.4.1 Definition

It has been argued that horizontal workplane illuminance data does not sufficiently describe the visual environment. Studies show that occupants' satisfaction with the interior lighting environment depends on a variety of factors including the nature of the task, the perceived brightness of the work task and surfaces surrounding the task, sources of glare, outdoor daylight conditions, and the direction, distribution, and source of light [Lee et al., 1998b]. It has been also argued that in modern office environments, developments in computer and desktop-publishing technologies have caused the primary work surface to shift from a horizontal desk surface to a vertical display screen surface [Osterhaus et al., 1992]. Most office workplaces now include visual display unit tasks, and lighting requirements for these contemporary vertical tasks differ considerably from conventional, more or less horizontal, reading and writing tasks [Sweitzer, 1991]. Although it is recommended that sight-lines to computer screens be parallel to windows [DETR, 1998b], as in Figure 4-10, limited space availability can result in inadequate positioning of computer screens in relation to windows and/or lighting installations, possibly resulting in excessive brightness, contrast, screen reflections, and discomfort glare.

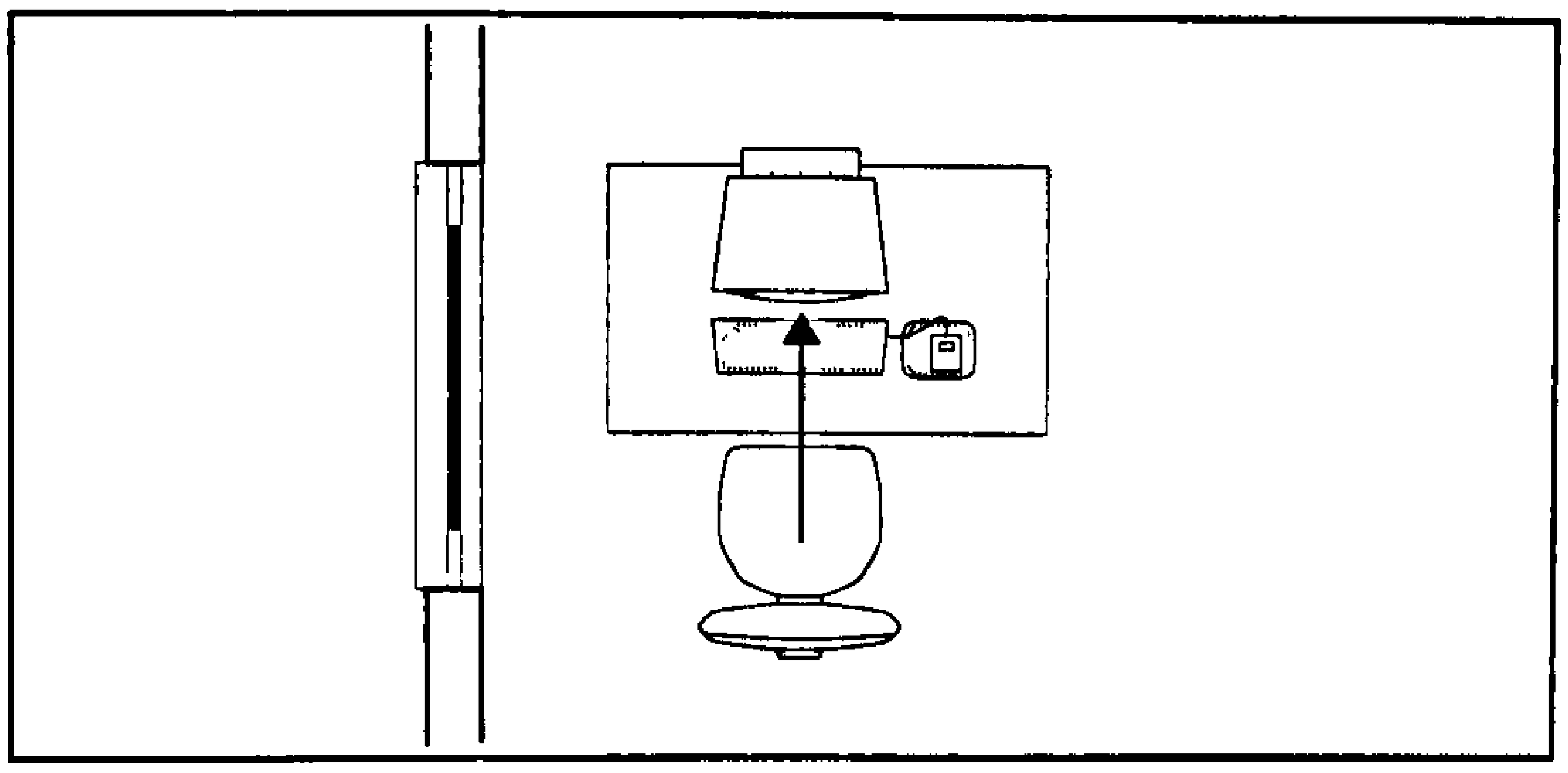

Figure 4-10 Recommended layout of computer screens relative to windows [re-drawn from DETR, 1998b]

Discomfort glare has been assessed in several studies by viewing and rating the glare source directly in conditions that simulate a worker looking up from a work task. However, it is being argued that for relevance to tasks of today's work environment, it seems important to more carefully consider situations in which the glare source occupies a substantial part of the visual field while subjects actually perform work tasks. The glare subjective rating, developed by Osterhaus et al., addresses these issues [Osterhaus et al., 1992].

The glare subjective rating, SR, is a measure of discomfort glare caused by viewing high or non-uniform luminance for visual display terminal (VDT) tasks. It is defined as

$$SR = 0.1909E_v^{0.31} \tag{4-1}$$

where E_v is the vertical illuminance facing the window (i.e., worst position for a VDT user) measured in the centre of the office at a seated eye level of 1.22 m.. For SR, a value of 0.5 defines the borderline between 'just imperceptible' and 'just noticeable', 1.5 defines the borderline between 'just noticeable' and 'just disturbing', and 2.5 defines the borderline between 'just disturbing' and 'just intolerable', as shown in Figure 4-11 [Lee et al. 2000b].

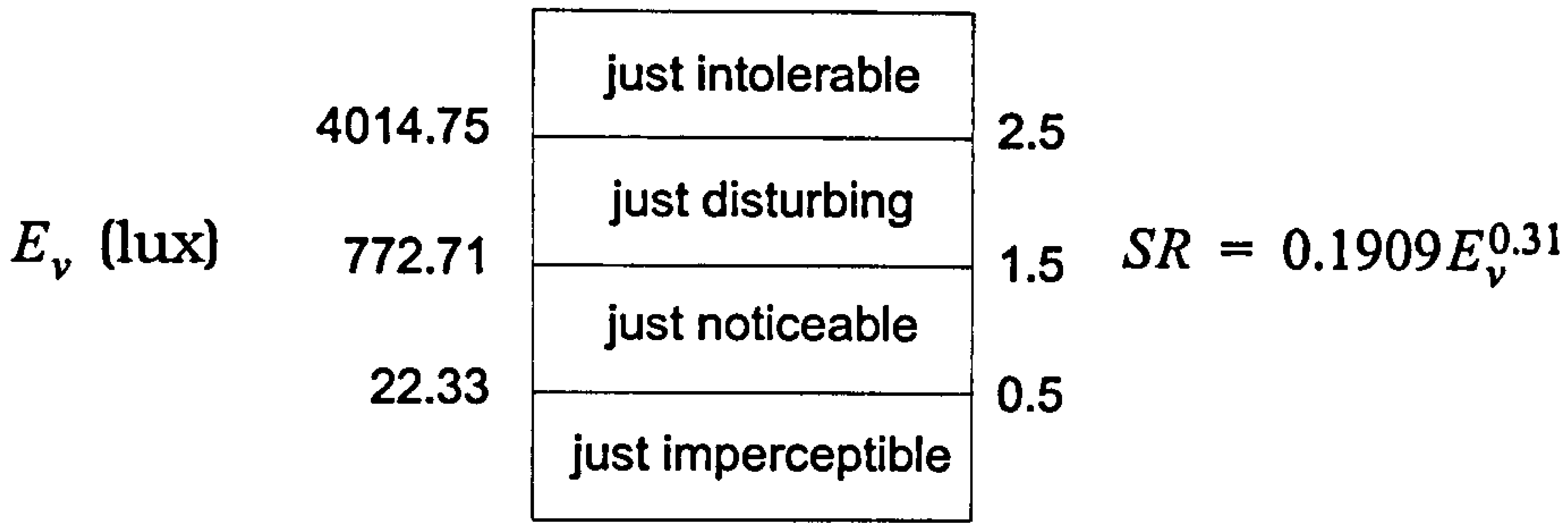

Figure 4-11 Glare subjective rating according to the definition by Osterhaus et al. [Osterhaus et al., 1992]

4.4.2 Application

Since the users' perception of the daylight conditions and the visual environment significantly determines whether a daylighting system is accepted and used appropriately [Christoffersen et al., 1997], glare subjective rating is employed in this study in order to obtain some measure of visual comfort. The distribution of glare subjective rating when the office model faces due south was calculated and is shown in Figure 4-12. However, instead of calculating SR in the middle of the office only (in this case, at 3 m. from the window) as per its definition, in this study, it was calculated along the whole depth of the office (i.e., front, middle, and back).

It can be seen from the figure that with clear double glazing, SR is 'just intolerable' 48.2%, 12.3% and 1.2% of the working year in the front, middle, and back of the office, respectively, while the corresponding 'just disturbing' values are 31.3%, 51%, and 45.1%, respectively. 'Just noticeable' values, on the other hand, are encountered only 10.8% of the working year in the front of the office, 26.6% in the middle, and 42.8% in the back. This indicates that, as would be expected, with an unshaded clear-glazed window facing due south, the visual environment for occupants in the office with VDT tasks facing the window can be considered uncomfortable (i.e., 'just disturbing' or 'just intolerable') most of the working year in the front and middle of the office, and to a lesser degree in the back.

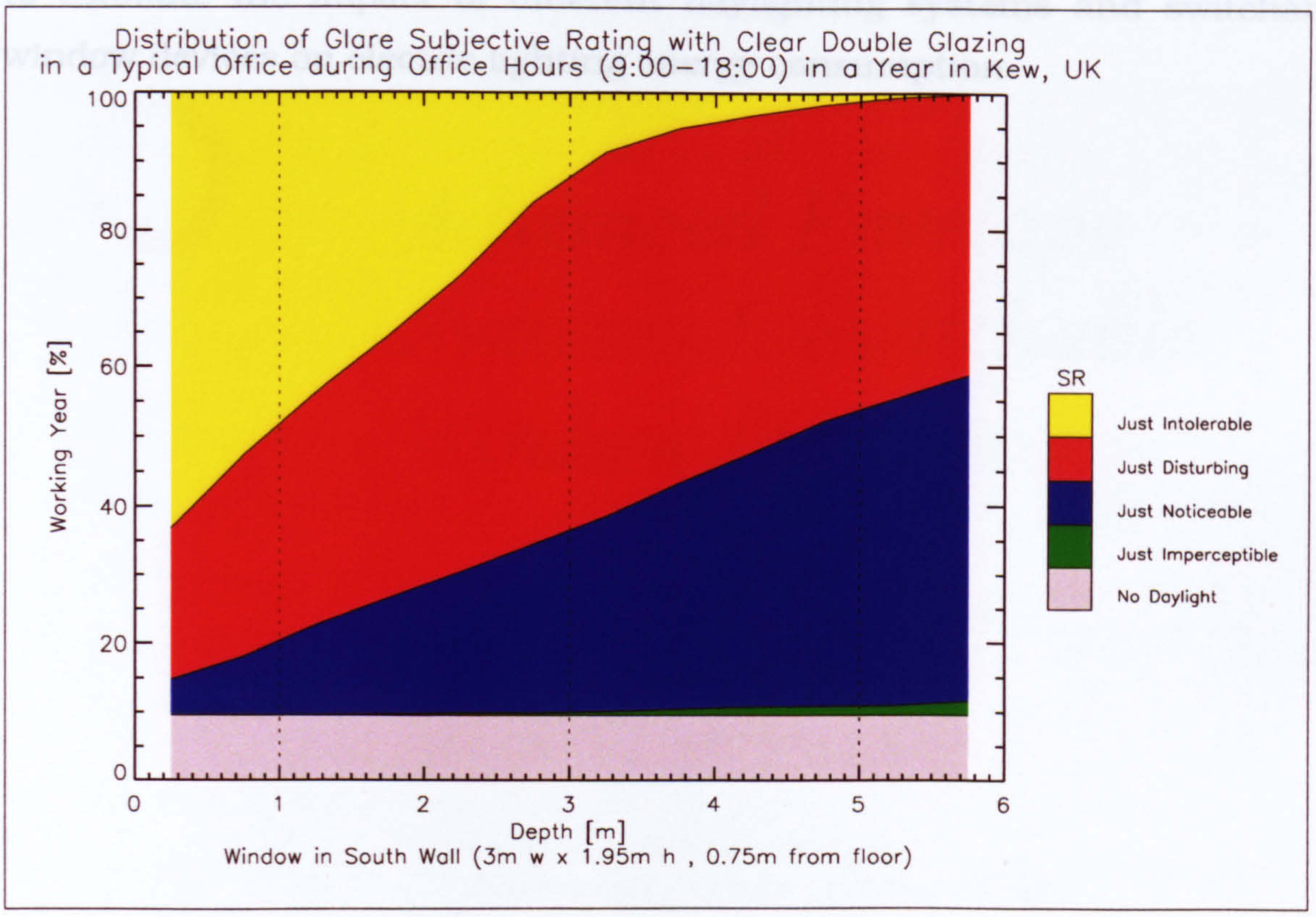

Figure 4-12 Glare subjective rating with a window of clear double glazing facing due south

4.5 Summary

The new metric for appraising daylight illuminance in office buildings, using the concept of useful daylight illuminances introduced in this chapter, was utilized in the rest of this study for the performance assessment of innovative envelope systems with regards to their impact on internal daylight illuminance. The metric was considered to combine the simplicity of DFs since it is a single quantity, the realism of DCs since it is based on real meteorological data and true azimuth orientation, and a degree of innovation since it describes the daylight illumination and uniformity along the depth of an office space and not just at a point.

The two values of net luminous efficacy for the electric lighting systems (33 lm/W for continuous dimming and 36 lm/W for on/off switching) and the methods described in Section 4.3 for calculating the total electric lighting energy requirements for the office were utilized during the rest of this study to estimate the impact of different daylighting systems and switchable window devices on electric lighting energy consumption.

Chapter

5

Advanced Envelope Systems I: Switchable Window Devices

"And not by eastern windows only,
When daylight comes, comes in the light,
In front the sun climbs slow, how slowly,
But westward, look, the land is bright."

ARTHUR HUGH CLOUGH 1819-1861 (*SAY NOT THE STRUGGLE NAUGHT AVAILETH*)

The wide variation in incident solar radiation and daylight availability, due to diurnal and seasonal changes in sun position and cloud cover, is considered a major cause of high energy use in buildings, peak demand, and occupants' discomfort [Lee et al., 1998b]. While conventional engineering design has usually adopted a static 'worst-case' perspective with respect to building envelopes, it has been argued that some type of dynamic control is called for when the internal environment in a building is required to be relatively constant while the external climate is highly variable. This is characteristic of daylight since external illuminance levels can change by a factor of 10 in a matter of seconds, as the sun moves behind a cloud for example, while it is necessary to maintain internal illuminance at relatively stable levels [Selkowitz, 1999].

Taking into consideration the high variability in external climate and the increased interest in creating large architectural spaces that are highly glazed (for example, atria, lobbies, and exhibition halls), much interest has focused on the control of the solar optical properties of glazing systems. The main two ambitions of research have been [Selkowitz, 1999]:

- The dynamic control of the intensity of transmitted heat and light in order to reduce glare, use of artificial lighting, and cooling loads.
- The dynamic optical control of light distribution within a space in order to moderate contrasts in internal illuminance. (Side-lit spaces, in particular, present problems of light distribution.)

As discussed earlier, this more dynamic view of building envelope performance requires that glazing and facade components are perceived as an integral part of an overall building system. The additional complexity and cost of a dynamic envelope system (compared to a conventional one) can be more readily justified if it results in energy savings with enhanced occupant comfort for a larger percentage of the year [Selkowitz et al., 1994].

In the following sections, the performances of different types of switchable envelope devices are simulated in order to examine their effects on the internal daylight illuminance and usage of electric lighting. First, simple daylight-linked manual operations of blinds and on/off switching of electric lighting are modelled. Then, more complex devices, such as daylight-linked automatic blinds, electrochromic glazing, and continuous dimming of electric lighting, are investigated. Different control strategies are tested, and the results are compared with one another. Comparisons are also made with the illuminance and energy results of the unshaded clear double glazing presented in the previous chapter (Chapter 4). The scenarios investigated are outlined in the schematic in Figure 5-1.

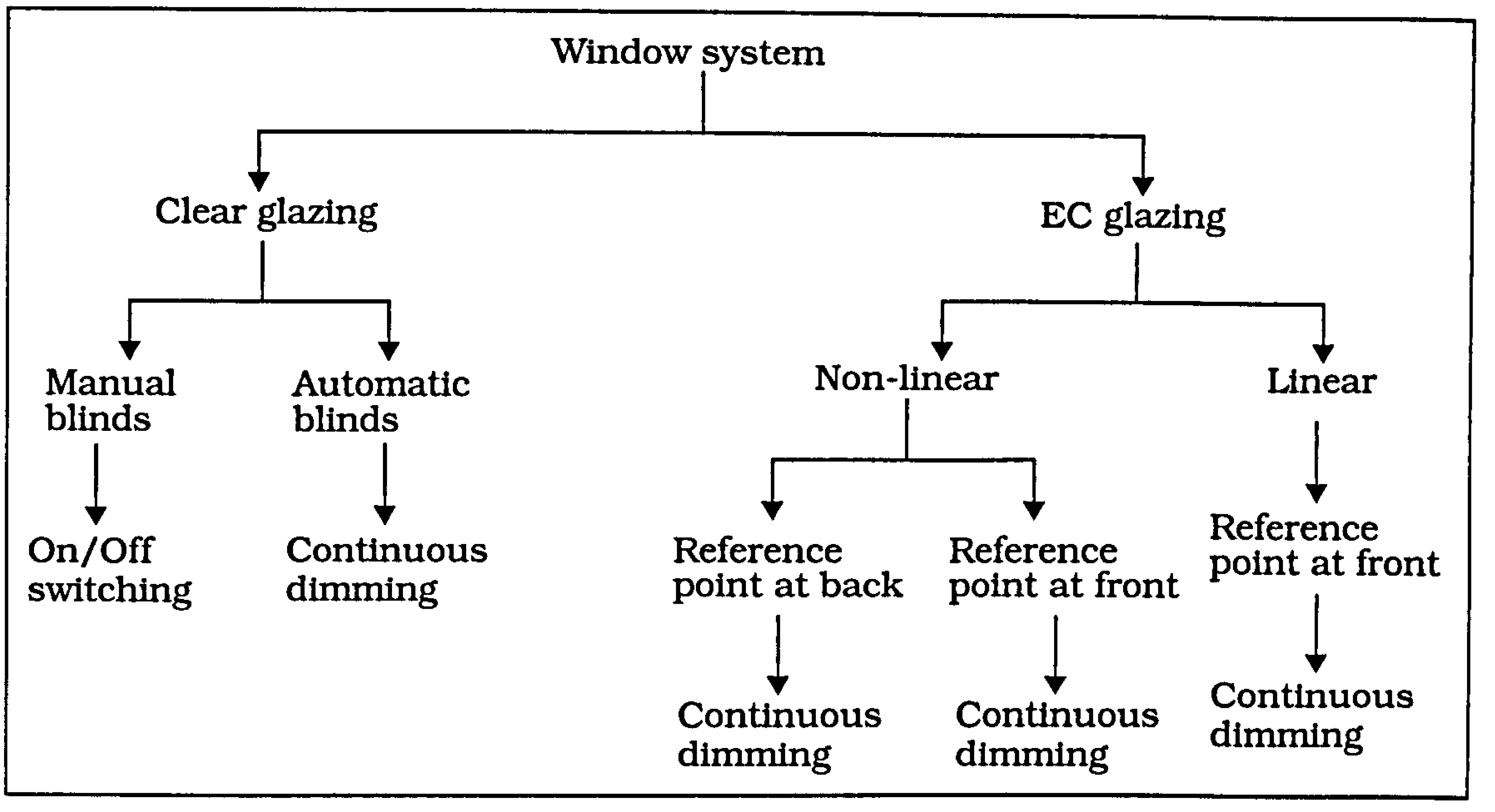

Figure 5-1 Schematic of window elements and associated electric lighting controls

Note that not all possible combinations of window device and lighting control are investigated. For example, it would not be reasonable to couple manual operation of blinds in a scenario with automatic continuous light dimming since the former is an unreliable/inconsistent method of controlling daylight admission that is solely dependent on occupants' behaviour, while the latter is a photosensor-controlled daylight-responsive process that can gradually and efficiently modulate illumination. The same is true for the unlikely scenario coupling manual on/off light switching with daylight-linked transmittance modulation of EC glazing.

Note also that the input to the models which simulate the effect of each of the switchable window devices is the same hourly daylight illuminances derived previously in Chapter 3 using the XDAPS formulation and the DCMs which were calculated for the office model, as outlined in the diagram of Figure 5-2.

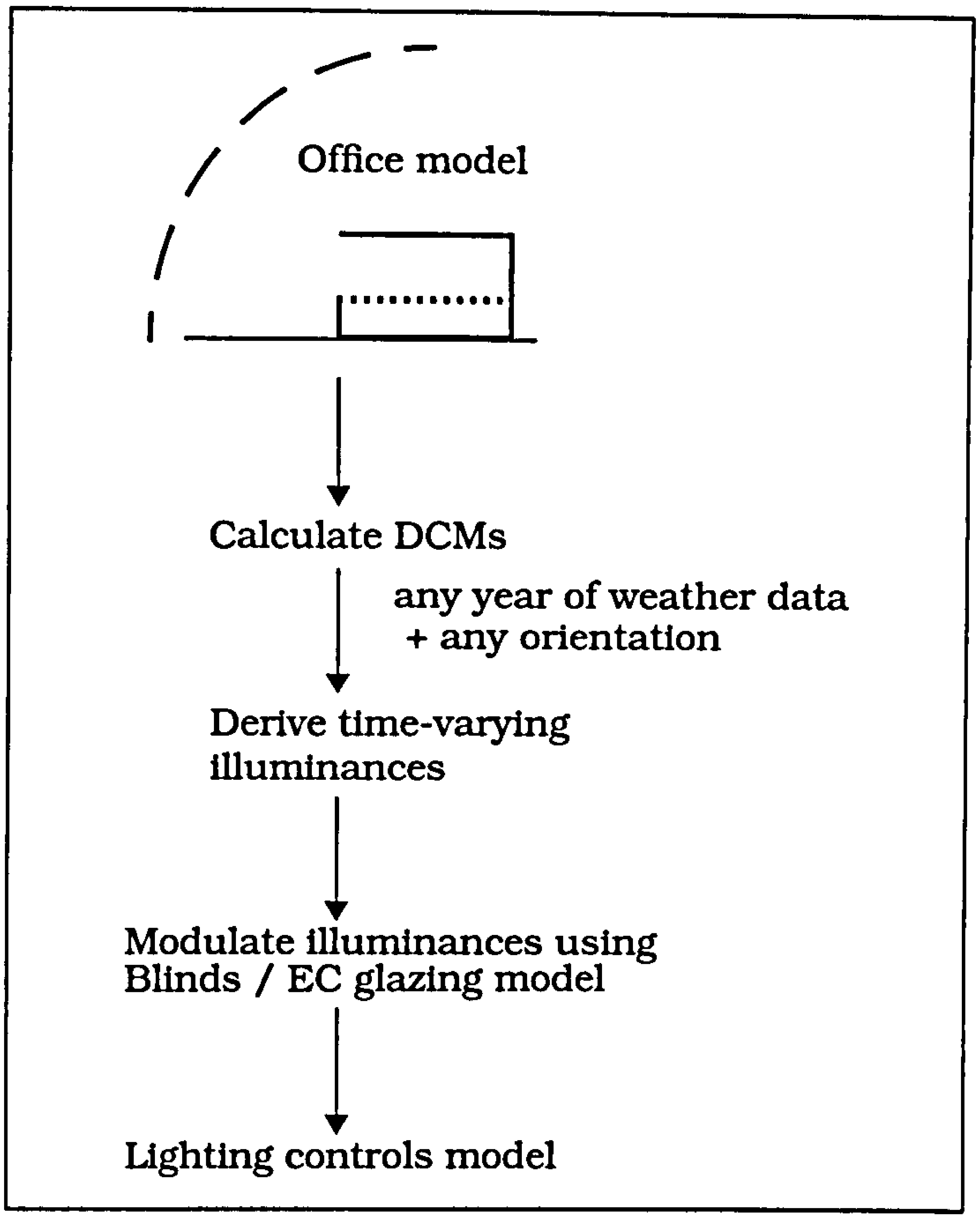

Figure 5-2 Process diagram

5.1 Modelling Shades and Blinds Performance

5.1.1 Blinds Operation and the Human Factor

It is argued that the success of any energy-saving strategy depends on the appreciation and the cooperation of the user [Reinhart, 2001]. Hence, the operation of a dynamic envelope system must cater to the preferences of the building occupants even if this can possibly reduce the attained energy savings. Where systems have failed to win the occupants' acceptance or have not accommodated their physiological (for example, thermal and visual comfort) and psychological (for example, view or contact with outdoors) criteria, there have been reports about systems which were misused, altered, disused, and even sabotaged by the occupants [Lee et al., 1994]. Such outcomes, thereby, weaken the support which is crucial for further development of these technologies and do not encourage designers, engineers, and architects to specify/recommend them in their proposed designs [Sweitzer, 1991][Lee et al., 1994].

Limited by the complexity of monitoring the movement of blinds, there are not many published studies on blind use. However, through the few that do exist, researchers argue that manually operated shading devices are rarely used effectively in real world applications [Lee et al., 1998c]. This is attributed to the notion that occupants tend to alter the position of the blind only when severely uncomfortable conditions occur, and that once a blind is lowered, it will usually take a substantial change in illuminance before the blind is raised again [Foster et al., 2001]. In addition, varying with buildings and occupants, there are some constraints/factors which influence the occupants' use of blinds. In some offices, for instance, occupants may always require the blinds to be down and shut for privacy reasons, or to avoid glare on visual display terminals. In other cases, individuals may not feel they could change the blinds' position in open plan offices for fear it might be displeasing to their colleagues.

Although blinds, like many other 'passive design strategies'[1], are very dependent on occupant control, expected occupant use is usually not realistically modelled in computer simulations. Designers employing these passive strategies assume that technical design decisions will be applied by the occupants as they were intended by the designer, i.e., appropriately to maximize environmental and energy benefits. However, studies show that this is often not the case, and that in real life applications, blinds are not always raised when there is little sun, and not necessarily lowered with high solar gains [Foster et al., 2001].

1. Passive design strategies are defined as the use of building design techniques to assist the natural heating or cooling of a building and so lessen or eliminate the need for heating or air conditioning. These strategies often include conservatories, atria, natural ventilation, thermal mass, shading, etc. [Foster et al., 2001].

5.1.2 Daylight Illuminance with Manual Blinds

Venetian blinds are familiar and widely available products. Nonetheless, in the context of simulation, they are regarded as optically and thermally complex systems due to their curved geometry and semi-specular surfaces [Lee et al., 1994]. Hence, whilst possible, detailed modelling of a Venetian blind system is considered computationally demanding as it requires the simulation of multi-reflected rays on small areas (i.e., the slats of the blind). As mentioned in section 2.1.3, however, reported field measurements reveal that approximately 20% of light penetrates Venetian blinds when they are fully drawn [Foster et al., 2001]. Therefore, in this study, blinds were modelled as simply neutral density filters which reduced daylight transmission by 80%. It should be noted that although modelling blinds only as either fully retracted or fully drawn (with no intermediate positions), in response to a threshold daylight illuminance value, might seem rather extreme and unrealistic, this was a simple model to implement and was useful for investigating a limiting case, i.e., fully drawn blinds.

As such, for the purpose for this study, a simple 'shutter' model was devised to simulate the 'ideal' manual operation of blinds/shades/screens by the office occupants whenever the daylight illuminance predicted at a point might be considered to cause discomfort. This shutter was triggered if the daylight illuminance at any of the 12 calculation points on the office's workplane (the same office model used previously in Chapter 3 and Chapter 4) exceeds a certain threshold value. Since this model was intended to simulate the manual operation of blinds, it was considered that discomfort experienced at any point along the length of the office could prompt the occupant at that point to operate the blinds[2] (thus affecting the illuminance in the whole office). The operation has been termed 'ideal' as it was modelled as perfectly daylight-linked, i.e., unlike in practical

2. Studies into manual use of blinds suggest that the general motivation for occupants to operate the blinds is to avoid glare rather than to prevent overheating, i.e., glare protection seems to be the main reason, followed by the avoidance of excessive heat gains [Reinhart, 2001].

situations, the blinds were always shut in response to the threshold illuminance and always retracted whenever shading was no longer required. As discussed in Section 4.2, the threshold daylight illuminance value was set at 2000 lux.

The hourly daylight illuminances predicted for all the points in the office (and used in generating the cumulative daylight availability in Figure 4-1) were examined, and at any of the 3650 hours in the working year (09:00 - 18:00) when the daylight illuminance at one or more calculation points in the office is predicted to exceed 2000 lux, all the illuminances at all the points for that hour were reduced by 80%, i.e.,

$$\begin{gathered} \textit{If}\,(\text{ illuminance at any point } > \text{ 2000 lux}) \\ \textit{Then}\,(\text{ illuminance at all the points } = \text{ illuminance at all the points } \times 0.2) \end{gathered}$$

Subsequently, similar to the procedure in Section 4.1.1, the numbers of hours in the working year, when 21 threshold values of illuminance (i.e., 0 lux, 100 lux, 200 lux, 300 lux,.... until 2000 lux) are exceeded, were computed for each of the 12 calculation points in the office. The numbers of hours were then each multiplied by $\frac{100\%}{3650}$ in order to give percentages of the working year. The results are presented for the main four azimuth orientations using false colours and contours in Figure 5-3.

As previously noted, dotted lines in the figure mark threshold illuminance values of 500 lux, 1000 lux, and 1500 lux and positions on the workplane 1 m., 3 m., and 5 m. from the window (for the front, middle, and back of the office, respectively). Corresponding sample percentages of daylight availability for these three points for the main four azimuth orientations are shown in Table 5-1.

Compared to the cumulative totals for an unshaded clear-glazed window in Figure 4-1 (and Table 4-1), Figure 5-3 demonstrates a big drop in daylight availability resulting from the operation of the shutter model. This indicates that for a large part of the working year, daylight illuminances of magnitudes more than 2000 lux are predicted at one or more points, and

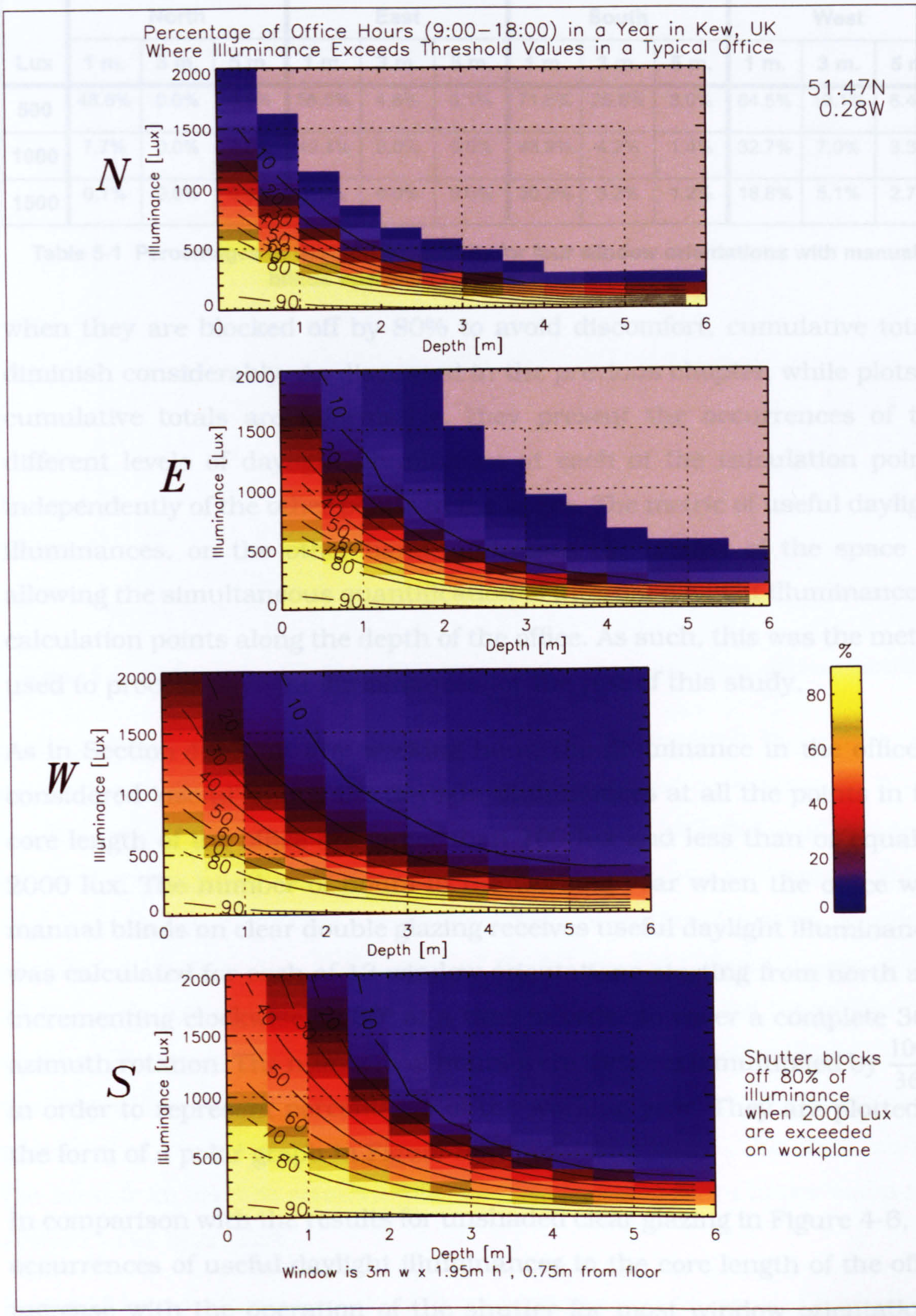

Figure 5-3 Cumulative illuminance availability for a line of 12 points on the workplane with manual blinds operation on clear double glazing

Lux	Percentage of Working Year											
	North			East			South			West		
	1 m.	3 m.	5 m.	1 m.	3 m.	5 m.	1 m.	3 m.	5 m.	1 m.	3 m.	5 m.
500	48.6%	0.0%	0.0%	55.5%	4.8%	0.1%	71.5%	25.6%	3.0%	64.5%	19.1%	6.4%
1000	7.7%	0.0%	0.0%	19.4%	0.0%	0.0%	46.9%	4.2%	1.4%	32.7%	7.0%	3.3%
1500	0.1%	0.0%	0.0%	7.3%	0.0%	0.0%	30.2%	3.2%	1.2%	18.8%	5.1%	2.7%

Table 5-1 Percentages of daylight availability for four window orientations with manual blinds operation on clear double glazing

when they are blocked off by 80% to avoid discomfort, cumulative totals diminish considerably. As discussed in the previous chapter, while plots of cumulative totals are informative, they present the occurrences of the different levels of daylight illuminance at each of the calculation points independently of the other points in the space. The metric of useful daylight illuminances, on the other hand, addresses the totality of the space by allowing the simultaneous quantification of internal daylight illuminance at calculation points along the depth of the office. As such, this was the metric used to process daylight illuminances for the rest of this study.

As in Section 4.2.2, at any working hour, the illuminance in the office is considered 'useful' only if the daylight illuminances at all the points in the core length of the office are larger than 100 lux and less than or equal to 2000 lux. The number of hours in the working year when the office with manual blinds on clear double glazing receives useful daylight illuminances was calculated for each of 12 window orientations starting from north and incrementing clockwise by 30° at a time in order to cover a complete 360° azimuth rotation. The numbers of hours were then each multiplied by $\frac{100\%}{3650}$ in order to represent percentages of the working year. They are plotted in the form of a polar graph in Figure 5-4.

In comparison with the results for unshaded clear glazing in Figure 4-6, the occurrences of useful daylight illuminances in the core length of the office increase with the operation of the shutter for most window orientations, which means that eliminating very high levels of illuminance, using the

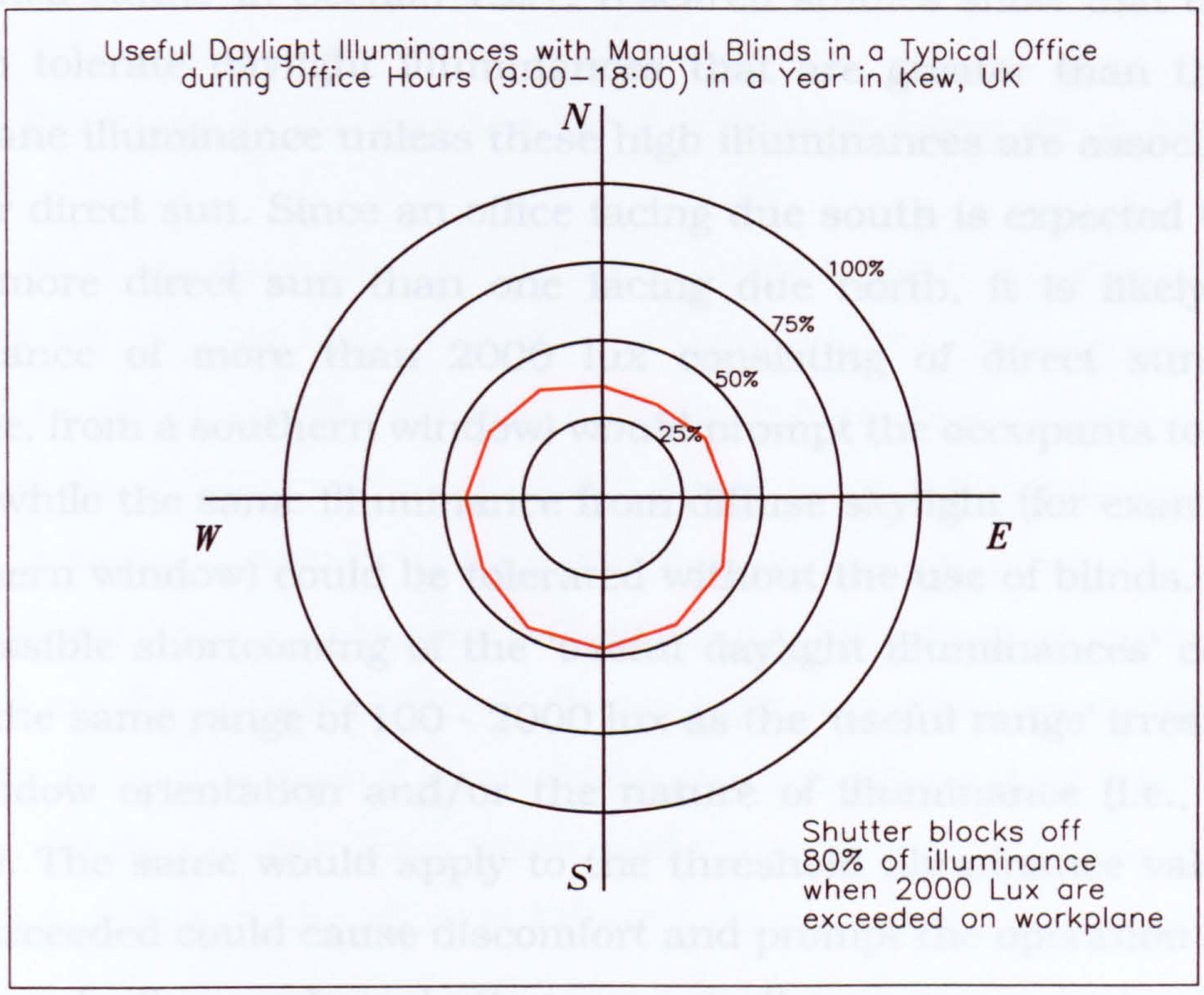

Figure 5-4 Useful daylight illuminances with operation of manual blinds on clear double glazing

shutter, results in more 'useful' daylight. The improvement is highest for the southern orientation, with useful daylight illuminances occurring 47.7% of the time with manual blinds instead of 17.6% with an unshaded window, followed by west with 43.1% instead of 24.6%, and then east with a small rise from 36.3% to 39.2%. An office with a northern window, however, sustains a drop in the availability of useful daylight illuminances, from 43.6% of the time with an unshaded window to 35.3% with the use of the shutter. The reason for this is probably that an unshaded window facing due north (in the northern hemisphere) receives daylight illuminances of much lower levels than the other orientations and would, therefore, suffer the most from an 80% reduction in the magnitude of illuminance when the shutter is in operation.

It should be noted that it is likely that occupants would respond to daylight illuminances higher than 2000 lux from a northern window in a way which is different to the same levels of illuminance from a southern window. As mentioned earlier in Section 4.2.1, research studies show that occupants tend to tolerate daylight illuminances that are greater than the design workplane illuminance unless these high illuminances are associated with glare or direct sun. Since an office facing due south is expected to receive much more direct sun than one facing due north, it is likely that an illuminance of more than 2000 lux consisting of direct sunlight (for example, from a southern window) would prompt the occupants to draw the blinds while the same illuminance from diffuse skylight (for example, from a northern window) could be tolerated without the use of blinds. Hence, it is a possible shortcoming of the 'useful daylight illuminances' concept to define the same range of 100 - 2000 lux as the 'useful range' irrespective of the window orientation and/or the nature of illuminance (i.e., direct or diffuse). The same would apply to the threshold illuminance value which when exceeded could cause discomfort and prompt the operation of blinds. Therefore, further work, including more studies on occupants' preferences, could be to investigate if different office orientations and/or nature of illuminance warrant the definition of different ranges of useful daylight illuminances.

Note that if studies do reveal that occupants respond differently to the same levels of daylight illuminance depending on the nature of the illuminance (direct or diffuse), this could be investigated using the same hourly daylight illuminances already derived for this study. Recall that the XDAPS implementation of DCs and *Radiance* (as discussed is detail in Section 3.2) involves the calculation of three daylight coefficient matrices, and, consequently, the derivation of four components of daylight illuminance, for the direct and indirect components of illuminance due to the sky and the direct and indirect components of illuminance due to the sun. These four components are then summed to provide the hourly daylight illuminances. Therefore, re-working the investigation of useful daylight illuminances to include the nature of the illuminance, as well as its magnitude, is certainly feasible with this formulation.

5.1.3 Electric Lighting for On/Off Switching with Manual Blinds

In order to study the impact of the manual operation of blinds on the use of artificial lighting, the electric lighting energy required for manual daylight-linked (i.e., ideal) on/off switching associated with the blinds operation was predicted. As detailed in Section 4.3.1, the average luminous efficacy of the electric lighting system at workplane level was taken to be 36 lm/W. For ideal daylight-linked manual on/off switching, the occupants were assumed to switch on the electric light, which provided a constant level of 500 lux, at any hour when this level of illuminance was not supplied by daylight alone. This means that at any hour when daylight at any point on the workplane falls below 500 lux, the electric lighting was assumed to be fully on, and otherwise, fully off. Separate switching was allowed for the front, middle and back luminaires in order to control lighting in the corresponding zones along the length of the office. The total electric energy, which is consumed annually by all three luminaires (per m^2 of floor area) due to on/off light switching, was calculated with the office window facing due each of 12 azimuth orientations. The orientations started from north and incremented clockwise by 30° at a time in order to cover a complete 360° azimuth rotation.

Because of the restriction on the movement of the shutter model, as mentioned earlier (either fully open or fully shut), in addition to the on/off lighting system (either fully on or fully off), the electric energy required for lighting is relatively high as seen in Figure 5-5 and Table 5-2 for the main four window orientations. Compared to the unshaded clear window in Figure 4-8, the lighting energy required to accompany the operation of manual blinds is almost double. This is because with no options for intermediate lighting intensities, whenever the daylight illuminance is less than 500 lux, the artificial lighting will always be fully on often resulting in

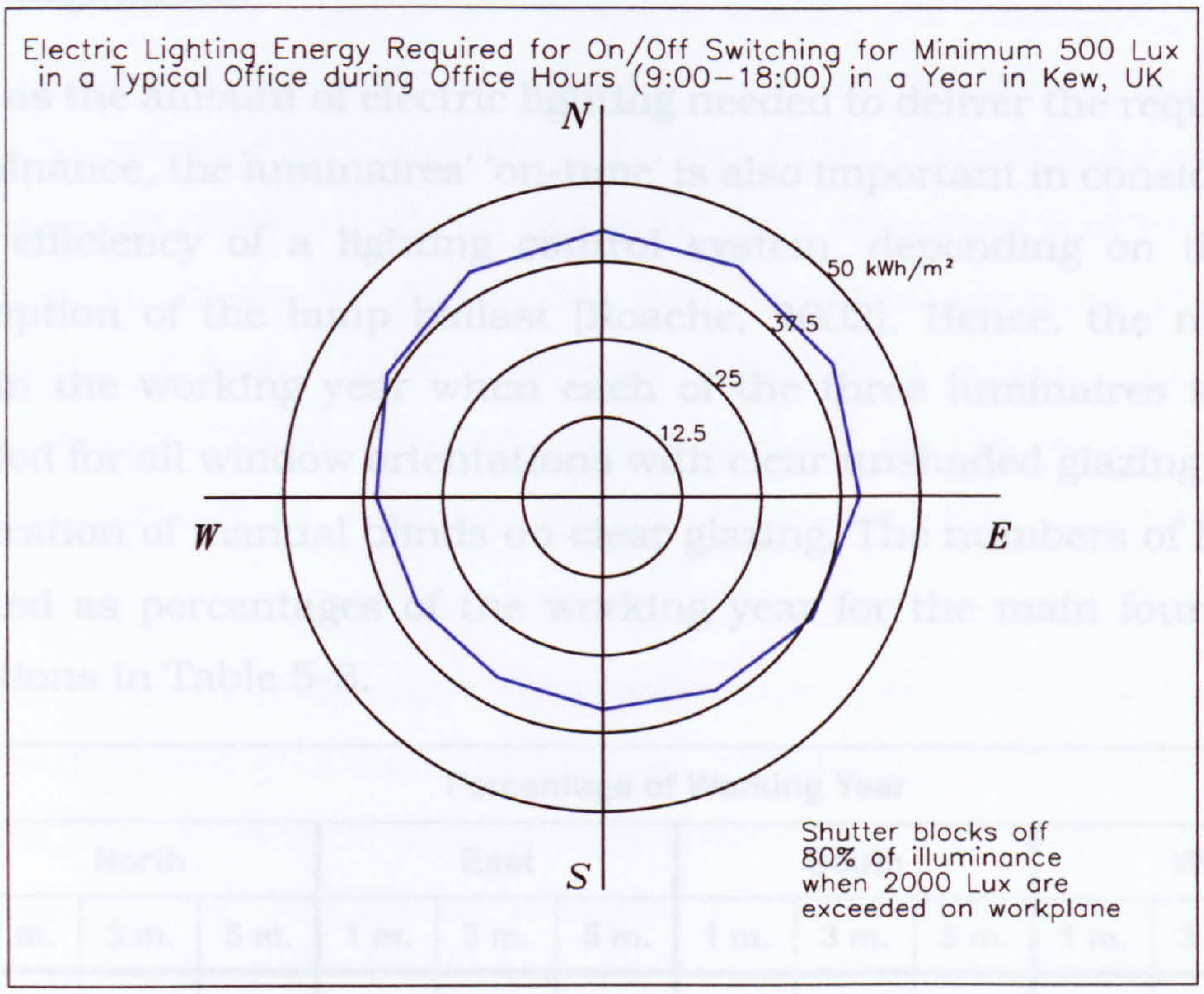

Figure 5-5 Annual lighting energy demand for on/off switching with operation of manual blinds on clear double glazing

Lighting Control and Window Status	kWh/m² North	East	South	West
On/Off switching with unshaded clear glazing	24.4	21.4	15.2	17.9
On/Off switching with manual blinds	42.5	40.5	33.8	35.5

Table 5-2 Artificial lighting energy demand in kWh/m^2 for on/off switching with clear unshaded glazing and with operation of manual blinds

a total illuminance which is higher than what is required. For example, if the predicted daylight illuminance is marginally above 2000 lux (say 2050 lux). The shutter is fully drawn, reducing the illuminance by 80% (410 lux). The artificial lights are then switched on providing 500 lux (giving a total of 910 lux). Recall that the above simulates ideal manual operation of artificial lighting, i.e., perfect synchronization with the available daylight, and that in practical (i.e., real life) situations, it cannot be guaranteed that the occupants will always switch off the lights as soon as they are no longer needed. Hence, energy consumption figures in practice are liable to be of higher magnitudes.

As well as the amount of electric lighting needed to deliver the required level of illuminance, the luminaires' 'on-time' is also important in considering the energy efficiency of a lighting control system, depending on the power consumption of the lamp ballast [Roache, 2002]. Hence, the number of hours in the working year when each of the three luminaires is on was computed for all window orientations with clear unshaded glazing and with the operation of manual blinds on clear glazing. The numbers of hours are presented as percentages of the working year for the main four azimuth orientations in Table 5-3.

	Percentage of Working Year											
	North			East			South			West		
Status	1 m.	3 m.	5 m.	1 m.	3 m.	5 m.	1 m.	3 m.	5 m.	1 m.	3 m.	5 m.
No Blinds	17.5%	45.6%	81.2%	16.3%	40.3%	70.0%	15.8%	29.5%	44.9%	16.7%	34.2%	55.2%
Blinds	51.4%	100%	100%	44.5%	95.2%	99.9%	28.5%	74.4%	97.0%	35.5%	80.9%	93.6%

Table 5-3 Percentage of working year when artificial lighting is on in an office with and without manual blinds on clear double glazing

In the case of manual blinds, the luminaire in the back of the office is on practically all the time during office hours for almost any orientation of the window (100% of the time for a northern or an eastern window, 97% for a southern window, and 93.6% for a western window). This is in comparison with 81.2%, 70%, 44.9%, and 55.2% of the time for an office with an unshaded window facing due north, east, south, and west, respectively. With manual blinds also, the luminaire in the middle of the office is on all or most of the time for the four azimuth orientations, instead of less than half the time in the case of unshaded clear glazing.

5.1.4 Daylight Illuminance with Automatic Blinds

Although manually operated Venetian blinds are commonly used in commercial buildings, as discussed earlier, their operation by the occupants tends to be considerably unreliable. For example, a recent survey[3] revealed that occupants often left blinds down for days after they had been needed (i.e., when the cause for discomfort was no longer present), resulting in extensive use of electric lighting [Roache, 2002]. This suggests that if a more reliable daylight-linked shading system is used on the window, such as automatic instead of manual blinds, greater energy savings can be expected.

There are some commercially available European and U.S. automated (motorized) shading systems (Venetian blinds and roller shades) that implement simple control strategies in order to limit the transmitted direct solar radiation, but only few are integrated with the lighting control systems (i.e., operation of artificial lights is left to the occupants) [DiBartolomeo et al., 1996]. A small direct-current motor at the base of the blind is used to alter the slats' angles. Tests are also being carried out to retract and lower prototype Venetian blinds (i.e., in addition to tilting the slats, in order to optimize workplane illuminance as well as provide maximum view out) and synchronize the blinds operation with lighting controls [Lee et al., 1999][Reinhart et al., 2001].

Unlike manual operation of blinds, where an occupant at any part of the office can operate the blinds when discomfort is sensed, a photosensor at a specific reference/control point in the office is needed to trigger a particular action from an automated blinds system. Although artificial lights can be controlled separately in different parts of the office (by separate luminaires), automated blinds (shading devices in general) usually cannot since the action affects the whole office. In an office side-lit by a window, a photosensor for the control algorithm is typically mounted on the ceiling to

3. The survey was undertaken within a project which studied the performance of an automated lighting and blinds control system [Roache, 2002].

determine the illuminance level at a reference point on the task workplane (as discussed in Section 2.3.3.1). In typical commercial installations, this reference point is taken to be along the centre line of the office, at workplane level, usually at a distance approximately equal to two thirds the depth of the office (measured from the window) [Selkowitz et al., 1994][DiBartolomeo et al., 1996].

To simulate the operation of automatic blinds, it was first necessary to determine the optimum level of daylight illuminance at the reference point which when exceeded would trigger the automated blinds to be drawn. Note that it was decided to optimize the operation of the automatic window device with respect to optimum daylight illumination rather than, for example, minimum electric lighting consumption. This is because, as discussed previously, if the illuminance and comfort requirements of the occupants are not met by such automatic systems, the systems are usually disabled (over-ridden) by the occupants, and any forecast energy savings are not actually achieved.

An optimization test was, thus, carried out in which 20 illuminance values were tested, ranging from 100 lux to 2000 lux, incrementing by 100 lux (i.e., 100 lux, 200 lux, 300 lux,.... until 2000 lux). The shutter model, utilized in Section 5.1.2 for manual blinds operation, was modified such that it was triggered (reducing daylight illuminances at all the points by 80%) at any of the 3650 hours in the working year when the workplane reference point, positioned at 4.25 m. from the window, receives an illuminance exceeding each one of the test values in turn, i.e.,

$$\textit{If}\,(\text{ illuminance at reference point } > \text{ test value})$$
$$\textit{Then}\,(\text{ illuminance at all the points } = \text{ illuminance at all the points } \times 0.2)$$

During the test, the number of hours in the working year when the office receives useful daylight illuminances was calculated for each of 12 azimuth orientations starting from north and incrementing clockwise by 30° at a time in order to cover a complete 360° azimuth rotation. The numbers of hours were then each multiplied by $\frac{100\%}{3650}$ in order to represent percentages of the working year. The results were scanned to determine for each window orientation, the value of daylight illuminance (out of the 20 tested values) at the reference point which when used to trigger the automated blinds results in the maximum percentage (i.e., biggest fraction) of the year during which the office is illuminated by useful daylight illuminances. The illuminance values at the reference point corresponding to maximum occurrences of useful daylight illuminances for each azimuth orientation are plotted in the form of a polar graph in Figure 5-6.

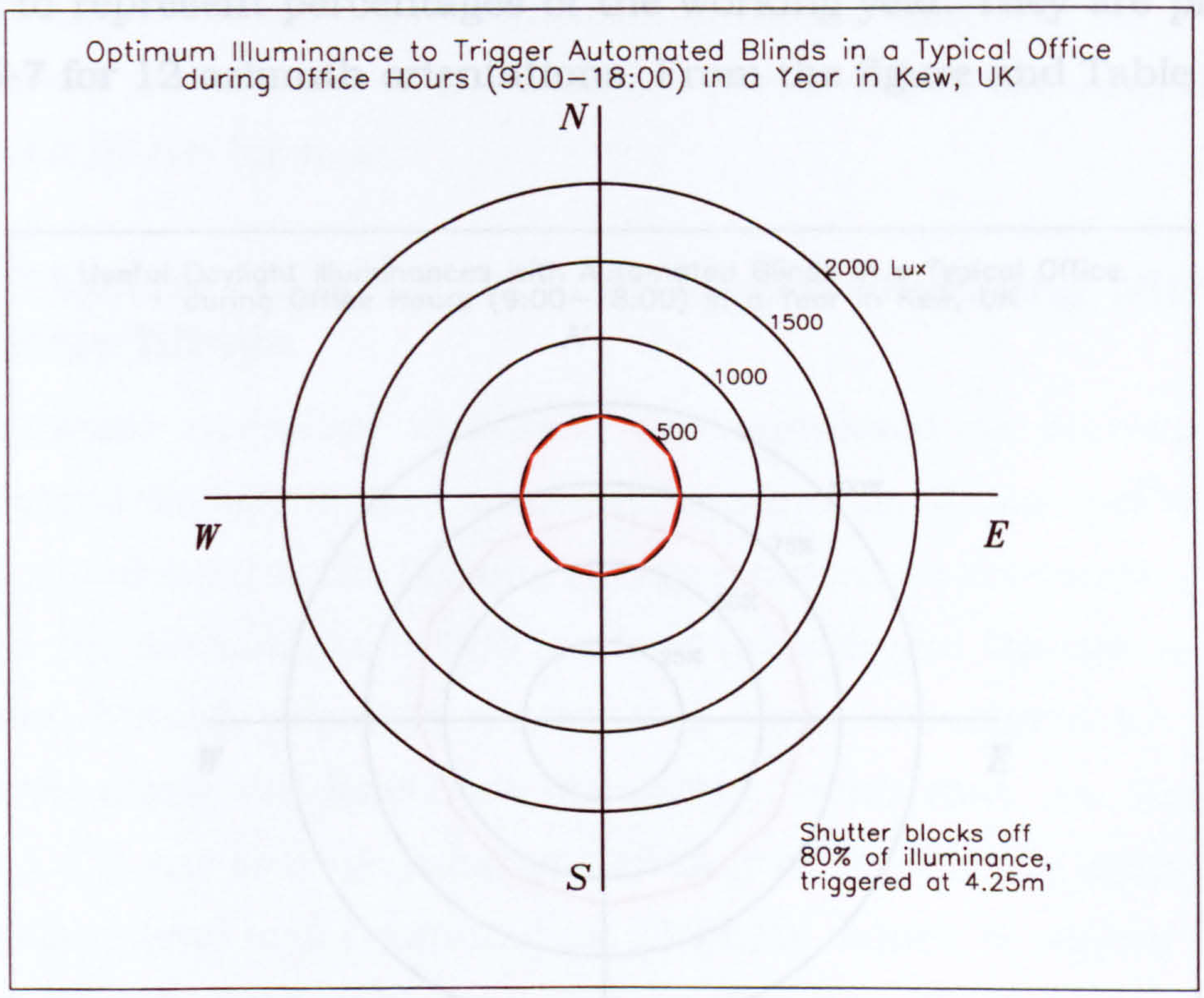

Figure 5-6 Testing for illuminance value, at the back of the office, to trigger automatic blinds operation and result in optimum percentage of useful daylight illuminances

Note that the illuminance value, which if used to trigger the operation of the automatic blinds results in the maximum occurrence of useful daylight illuminances, is the same for all azimuth orientations, 500 lux. Hence, in order to simulate automated blinds, the shutter was modelled in such a way that at any of the 3650 hours in the working year when the daylight illuminance at the reference point is predicted to exceed 500 lux, the illuminances at all the points for that hour were reduced by 80%, i.e.,

$$\textit{If}\ (\text{ illuminance at reference point} > 500\ \text{lux})$$

$$\textit{Then}\ (\text{ illuminance at all the points } = \text{illuminance at all the points} \times 0.2)$$

The number of hours in the working year when the office with automatic blinds receives useful daylight illuminances was calculated for each of 12 azimuth orientations for the office window starting from north and incrementing clockwise by 30° at a time in order to cover a complete 360° azimuth rotation. The numbers of hours were then each multiplied by $\frac{100\%}{3650}$ in order to represent percentages of the working year. They are plotted in Figure 5-7 for 12 azimuth orientations. From the figure and Table 5-4, the

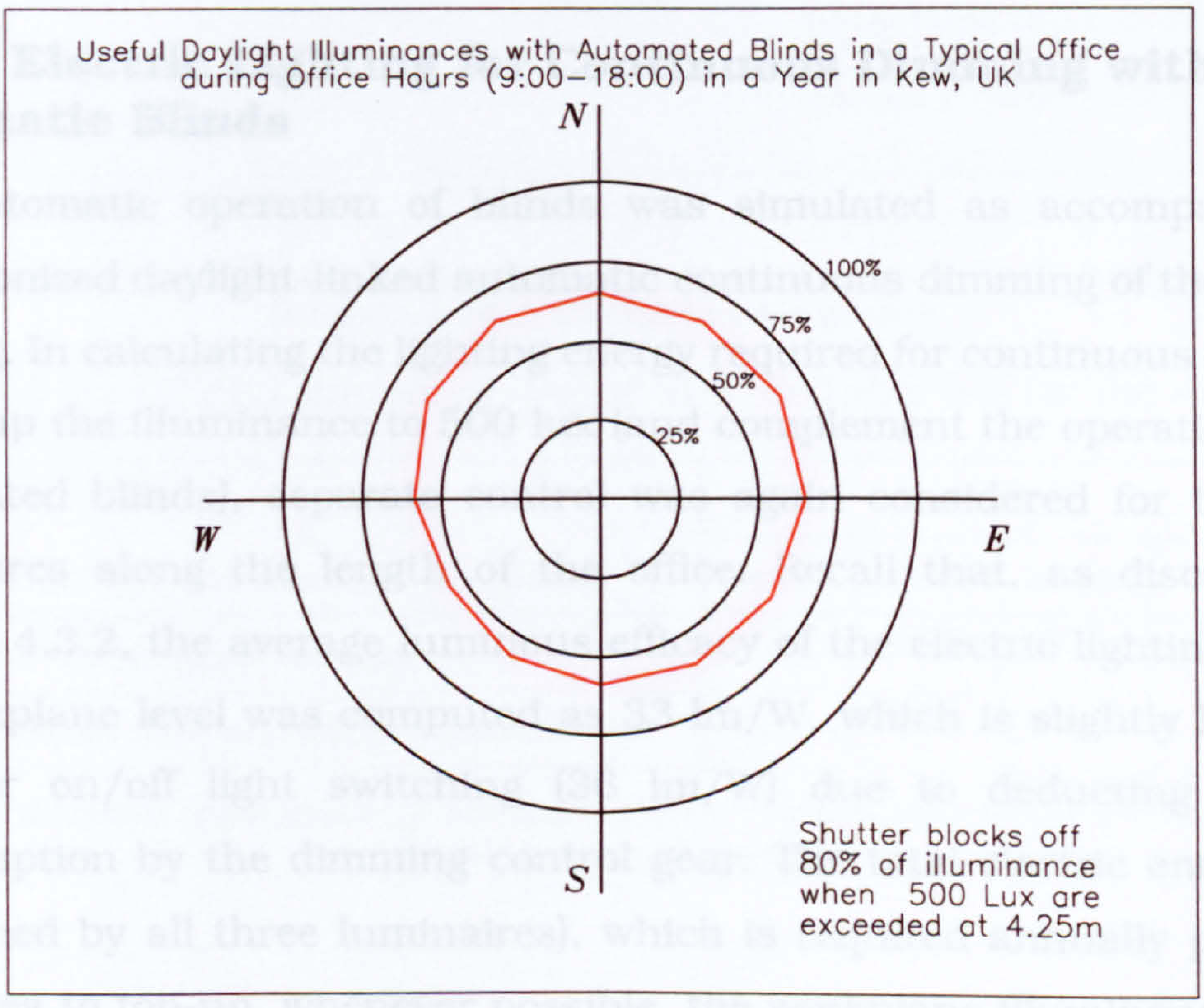

Figure 5-7 Useful daylight illuminances with operation of automatic blinds, referenced to a point at the back of the office

overall improvement (i.e., more occurrences of daylight illuminances throughout the working year) in the office's daylight illuminance when

Window Status	Percentage of Working Year			
	North	East	South	West
Unshaded clear glazing	43.6%	36.3%	17.6%	24.6%
Manual blinds	35.3%	39.2%	47.7%	43.1%
Automated blinds	65.3%	64.8%	58.8%	58.6%

Table 5-4 Occurrences of useful daylight illuminances without shading and with the operation of manual and automatic blinds on clear double glazing

using automated blinds can be observed, compared to manually operated blinds or an unshaded window. With automated blinds, useful daylight illuminances occur during more than half the working year for all window orientations, with 65.3% of the time for north, 64.8% for east, 58.8% for south, and 58.6% for west.

5.1.5 Electric Lighting for Continuous Dimming with Automatic Blinds

The automatic operation of blinds was simulated as accompanied by synchronized daylight-linked automatic continuous dimming of the electric lighting. In calculating the lighting energy required for continuous dimming to top up the illuminance to 500 lux (and complement the operation of the automated blinds), separate control was again considered for the three luminaires along the length of the office. Recall that, as discussed in Section 4.3.2, the average luminous efficacy of the electric lighting system at workplane level was computed as 33 lm/W, which is slightly less than that for on/off light switching (36 lm/W) due to deducting 10% as consumption by the dimming control gear. The total electric energy (i.e., consumed by all three luminaires), which is required annually per m^2 of floor area to top-up, whenever possible, the workplane illuminance to 500 lux, was calculated with the office window facing due each of 12 azimuth orientations. The orientations started from north and incremented clockwise by 30° at a time in order to cover a complete 360° azimuth rotation. The results are shown in Figure 5-8 and then compared to those

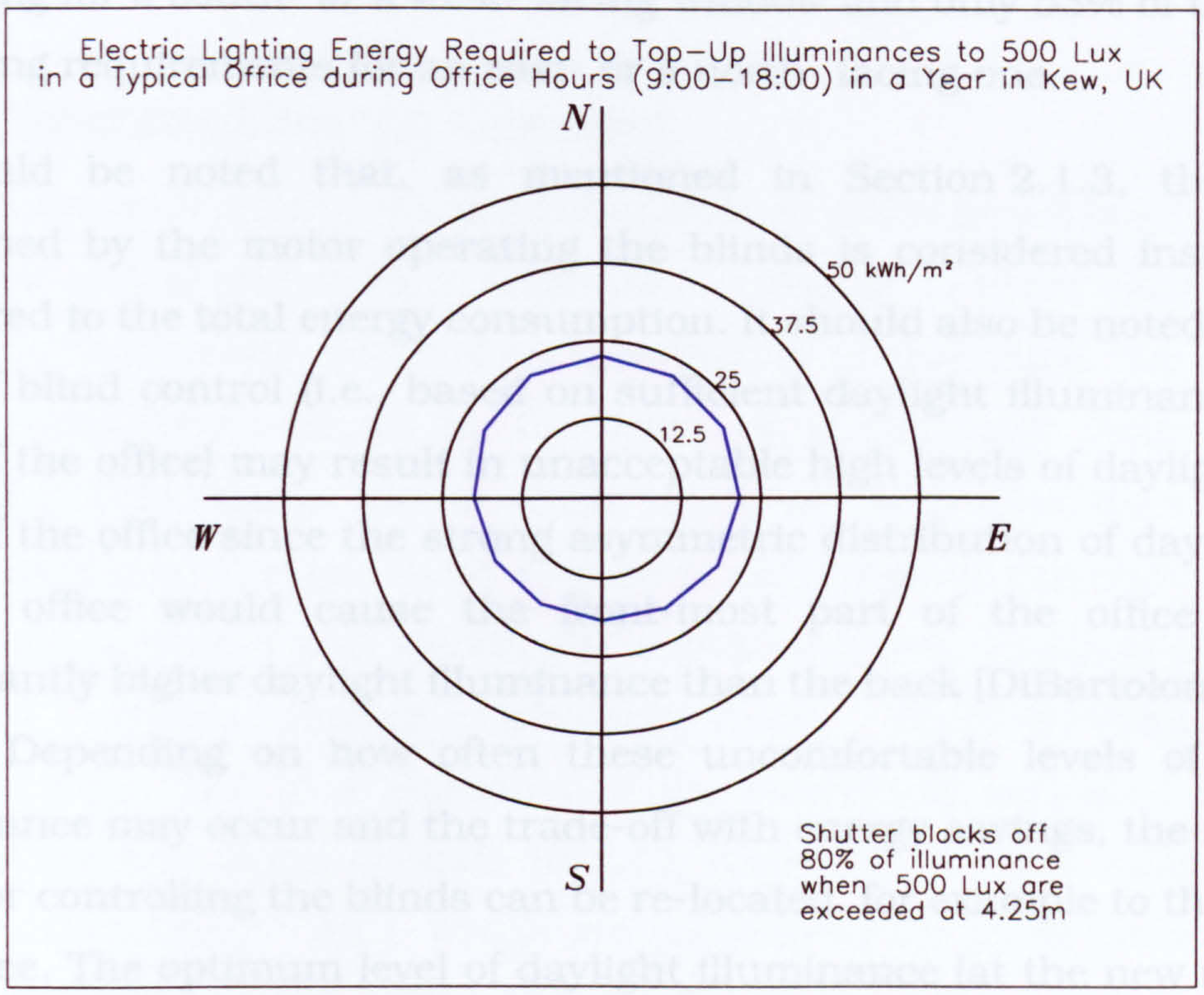

Figure 5-8 Annual lighting energy demand for continuous dimming control with automatic blinds operation on clear double glazing

of manual on/off light switching (Figure 5-5) in Table 5-5 for the main four

Lighting Control and Window Status	kWh/m²			
	North	East	South	West
On/Off switching with manual blinds	42.5	40.5	33.8	35.5
Continuous dimming with automated blinds	22.5	21.7	19.2	20.1

Table 5-5 Artificial lighting energy demand in kWh/m² for on/off switching and continuous dimming control systems

azimuth orientations.

Predictably, energy consumption of daylight-linked automatic continuous dimming light controls accompanying the operation of automatic blinds is much less than daylight-linked manual on/off switching accompanying the operation of manual blinds. In fact, in this case, consumption due to continuous light dimming requires only 57% of that required by light on/off switching for a south- or a west- facing window and only 53% of the on/off switching requirements for an east- or a north- facing one.

It should be noted that, as mentioned in Section 2.1.3, the energy consumed by the motor operating the blinds is considered insignificant compared to the total energy consumption. It should also be noted that this kind of blind control (i.e., based on sufficient daylight illuminance at the back of the office) may result in unacceptable high levels of daylight at the front of the office since the strong asymmetric distribution of daylight in a side-lit office would cause the front-most part of the office to have significantly higher daylight illuminance than the back [DiBartolomeo et al., 1996]. Depending on how often these uncomfortable levels of daylight illuminance may occur and the trade-off with energy savings, the reference point for controlling the blinds can be re-located, for example to the front of the office. The optimum level of daylight illuminance (at the new reference point) to trigger the operation of the blinds can then be determined using an optimization test similar to the one in Figure 5-6. Although re-locating the reference point may cause a reduction in energy savings, it should be noted that there have been reports that in cases when the automated system does not satisfy the visual requirements of the occupants, they have resorted to disabling the controls, resulting in more consumption of energy (than that forecast due to system adjustments which may accommodate occupants' preferences) [Lee et al., 1994]. This is a sign of the conflict, referred to earlier, that could arise between energy saving measures and occupants' comfort. Therefore, to render any control strategy practically successful, compromises have to be sought, and further studies on occupants' behaviour are required.

While automated Venetian blind systems may be suitable for specific envelope control strategies, variable transmission glazings (made of 'chromogenic' material) are regarded as a more refined realization of smart envelope systems [DiBartolomeo et al., 1996]. These innovative devices are investigated in the following section.

5.2 Electrochromic Glazing

The fundamental feature of a chromogenic material is that it exhibits a large change in optical properties in response to a change in either electrical field, charge, light intensity, spectral composition, or temperature. The change in optical properties can be in the form of absorbance, reflectance, or scattering. This change can be either totally or partly over the visible and solar spectrums. The two main classes of chromogenic materials are non-electrically activated and electrically activated types. The non-electrically activated types include photochromics, thermochromics, and thermotropics. The most common of the electrically activated types are phase dispersed liquid crystals (PDLC), dispersed particle system (DPS), and electrochromics[4] (EC), which are considered the most promising and most complex [Lampert, 1995]. ECs are the focus of this section.

Unlike conventional glazings, electrochromics present an opportunity to optimize the energy and comfort performance of windows by dynamically and gradually varying their optical properties to fulfil the requirements of occupants and/or respond to the changing external climatic conditions. It is envisaged that ECs can reduce lighting loads by maintaining a sufficiently high visible transmittance to render a pleasant daylit environment inside but also provide glare control when needed [Sullivan et al., 1996a]. It is also hoped that EC windows can reduce cooling loads by providing better management of the thermal environment [Lee et al., 1998b]. As noted earlier, since the amount of total electric energy use in commercial buildings has a strong correlation with lighting energy use, then good daylighting performance is expected, in principle, to result in an efficient overall electric energy performance of the building [Sullivan et al., 1996a]. Optimizing comfort, however, may require some trade-offs with maximizing energy

4. Electrochromism occurs in organic, inorganic and polymer materials [Lampert, 1995].

savings. These trade-offs, it should be noted, are difficult to specify, and the amount of system control given to occupants and the energy-efficiency consequences of doing so are the subject of on-going discussion and debate [Lee et al., 1998b][Lee et al., 2000a].

Electrochromics have received considerable attention recently by governmental and industrial organizations, and a number of international research groups are investigating electrochromic materials and devices for building windows (some EC applications for smaller areas such as car windows, sunroofs, and rear-view mirrors are already available commercially) [Sullivan et al., 1996b][Lampert, 1995].

5.2.1 Composition of EC Glazing

An EC window consists of up to seven layers of materials. The fundamental function of the device results from the transport of hydrogen or lithium ions from an ion storage layer, and through an ion conducting layer, injecting them into an electrochromic layer, and vice versa. The electrochromic layer is typically tungsten oxide[5] (WO_3). The central three layers are 'sandwiched' between two layers of a transparent conducting oxide material as shown in Figure 5-9. To protect the five layers of materials, they are further sandwiched between two layers of glass.

To darken or colour the window, a small DC voltage is applied across the two transparent conducting oxide layers. This voltage drives the ions from the ion storage layer through the ion conducting layer and into the electrochromic layer. The presence of the ions in the electrochromic layer changes its optical properties, causing it to absorb visible light. The large-scale (i.e., overall) result is that the window darkens. To reverse the process, the voltage is reversed, driving the ions in the opposite direction, out of the electrochromic layer, through the ion conducting layer, and into the ion

5. The two materials widely used in electrochromic devices are tungsten oxide and lithium nickel oxide [Von Rottkay et al., 1996].

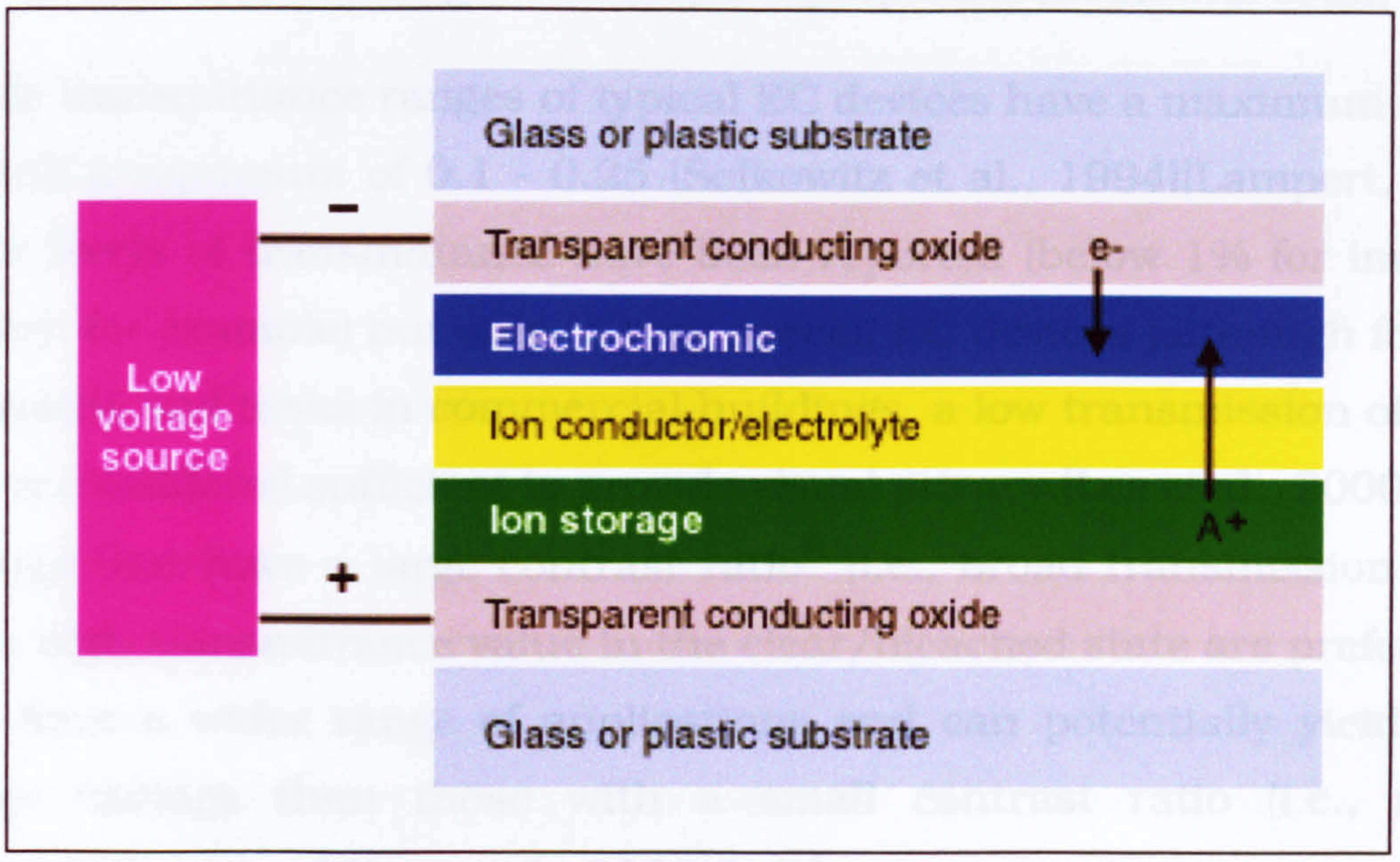

Figure 5-9 A cross-section of an electrochromic window [NREL, 2001].

storage layer. As the ions migrate out of the electrochromic layer, it lightens or bleaches, and the window becomes transparent again.

The ideal electrochromic (EC) window is an insulating double-glass unit with an EC coating on the inner surface of the outer pane and a reflective low-E glazing inner pane [Lee et al., 1998b]. In addition to windows and vertical glazing, the EC technology can potentially be assimilated into skylights, overhangs, louvres, light shelves, and other fenestration elements.

5.2.2 Characteristics

Electrochromics have two affiliated functions in a daylighting design strategy: switching over the entire solar spectrum to potentially control total solar gain, and switching in the visible fraction of the spectrum to control admitted daylight levels and glare [Selkowitz et al., 1994]. The most commonly available information in the literature, however, concerns EC transmittance over the visible spectrum only. The spectral switching properties of a specific EC window depend on the materials used, the overall coating design, and the whole glazing system, which may contain other glazing layers with coatings or absorptive properties [Selkowitz et al., 1998].

Visible transmittance ranges of typical EC devices have a maximum of 0.5 - 0.8 and a minimum of 0.1 - 0.25 [Selkowitz et al., 1994][Lampert, 1995]. Lower levels of transmittance have been reported (below 1% for improved privacy, for example) but only in very special EC devices (although for most occupants and tasks in commercial buildings, a low transmission of 0.06 - 0.11 is considered sufficient to provide visual privacy [Lee et al., 2000b]). EC glazings that have a large contrast ratio[6] (i.e., broad transmission range) and a high transmittance value in the clear/bleached state are preferred as they have a wider range of applications and can potentially yield larger energy savings than those with a small contrast ratio (i.e., narrow transmission range) [Lee et al., 2000a]. A large contrast ratio means the EC device has a large range of available transmittance values which allows more flexibility in responding to the continually varying sun and sky conditions.

The reported switching time of EC coatings to darken is typically 30 - 120 seconds, and the required switching voltage is 1 - 5 V [Selkowitz et al., 1998][Lampert, 1995]. It should be noted, however, that switching speed is material, size, and temperature dependent (it decreases with increased glazing area and when glazing is cold[7]), and it is higher (by 25 - 40%) from coloured to bleached than bleached to coloured [Lee et al., 2000b]. EC switching rate is also exponential, i.e., EC glazing achieves ~50% of its total change in colouration within ~25% of total switching time [Lee et al., 2000a].

The amount of electricity required to trigger the changes in EC glazing transmittance is considered negligible. In practice, the total consumption of electric energy is reported to be less than 1 kWh/m^2.year [Sweitzer, 1991]. Many EC devices have an open circuit 'memory' of a few hours (12 - 48

6. Contrast ratio is the ratio of maximum transmission to minimum transmission [Lee et al., 2000a].
7. Therefore, heating caused by direct solar irradiation can improve speed [Lee et al., 2000b].

hours or more) during which they can maintain a set state of transmission without requiring corrective voltage pulses. Future developments are called for in designing the appropriate materials to make EC devices durable over many years (20 - 30) and cycles (50,000 or more) and resistant to moisture, UV, and changing temperatures[8] (-30 - 80°C) [Lampert, 1995][Lee et al., 2000a].

The solar/optical properties of EC windows can be changed using control variables such as incident or transmitted solar radiation, daylight illuminance, ambient air temperature, or space thermal load [Sullivan et al., 1996b]. In this study, the performance of EC windows with respect to transmittance over the visible spectrum only will be investigated. Hence, daylight illuminance (i.e., daylight control) will be used as the control variable for EC performance testing, as detailed in the following sections. It should be mentioned that previous studies, using much simpler daylight algorithms, suggested that daylight control of EC switching provided the best overall energy performance because of the large reduction in the required electric lighting energy due to daylighting [Sullivan et al., 1994].

It should be also noted that, at present, the electrochromic window is being designed by most electrochromic developers as a stand-alone fenestration product, but it is believed that, as with other dynamic envelope devices, the proposed energy efficiency benefits can only be attained through its integration with daylight-linked lighting controls and through adequate resolution of possible contradictions between human preferences and energy efficiency objectives [LBNL, 2001]. It has been reported that daylighting systems in use rarely result in the energy savings which are predicted by simulation tools and which are believed to be achievable in real buildings. This has been primarily attributed to that window and artificial lighting systems are usually not designed and operated as an integrated system [Lee et al., 1998a]. Hence, this issue is addressed in Section 5.3.

8. Thermal cycling may have a considerable damaging effect on the performance or lifetime of electrochromic coatings [Selkowitz et al., 1994].

5.2.3 PV-EC Windows

A smart/dynamic window which has its own power source and no external wiring could be appealing. Since PV technology is progressively being introduced into building facades, one of the reported developments has been the use of small PV modules to provide local power to a motorized shade or Venetian blind [Selkowitz, 1999]. A variant of this idea is an integrated photovoltaic-powered electrochromic (PV-EC) window.

Two possible PV-EC window geometries are currently under development. The first is a side-by-side geometry, in which the window frame is covered with PV cells, and the second is a monolithic design, in which the EC layers are deposited on top of the PV layers. While the former device may be regarded as relatively uncomplicated, the fabrication of the latter is considered highly challenging, and there is a considerable body of research on it [Deb, 2000][Gao et al., 1998]. The monolithic tandem/stacked PV-EC device requires a semi-transparent PV coating that still produces enough voltage to drive the EC device and enough current to operate the device at a reasonable speed. The main technical challenge is considered to be in reducing the thickness of the PV device to less than 100 nm. in order to achieve sufficient semi-transparency. However, when semi-transparent PV devices become exceedingly thin, the top contact may short the PV device more easily yielding the stacked device useless [Deb, 2000]. Hence a monolithic PV-EC structure requires particularly careful design and fabrication.

5.3 Modelling EC Glazing Performance

Large-area electrochromic windows[9] have very recently become available in limited quantities, and research is currently being conducted to determine how they will perform in buildings [Lee et al., 2000a]. Previous investigations, both simulations using simple daylight modelling algorithms

9. Pilkington is currently the only manufacturer able to produce large-area electrochromic devices at a quality level that is acceptable for human factors evaluations [LBNL, 2001].

and field studies on prototypes of electrochromic windows, have usually been conducted with the controls set up in such a way that the optical properties of the EC glazing are modulated between bleached and coloured states in order to maintain a daylight illuminance of 500 lux at a reference point located along the centre line of a side-lit office, at workplane level and at a distance equal to two thirds the depth of the office [Selkowitz et al., 1994][Sullivan et al., 1996b][Lee et al., 2000b]. However, as mentioned earlier, this location for the reference point to control dynamic window devices is probably far from ideal since maintaining that level of illuminance at the back of a side-lit office means subjecting the front of the office to potentially uncomfortable high illuminances. This outlines what is possibly a drawback of typical design concepts/practices. It provides a clue as to why predicted energy savings forecast by simulations of innovative fenestration devices are often not achievable. This is due to the following:

- The fundamental aim of an orthodox design is usually to establish a solution to what is perceived as the worst case scenario, i.e., provide the required illuminance in the zone of the space where the illuminance level is normally the lowest (for example, the back of a side-lit space), regardless of the rest of the space (i.e., middle and front). In other words, assuming that if the illuminance at the back of the space is made to be sufficient, then the design problem is solved, and the illuminance in the rest of the space will be adequate by default.
- Generally assuming that as long as the illuminance is higher than the required 500 lux, then it is 'good' illuminance.
- Assuming that the occupants would necessarily accept the installed system and operate it as intended by the designer in order to provide energy savings.
- Making the energy consumption calculations based on the above optimistic assumptions.

As such, in the following sections, the metric of useful daylight illuminances, first introduced in Chapter 4 and then applied in studying blinds in the previous sections, is utilized as a more realistic tool for assessing the performance of EC windows with regards to internal illuminance and lighting energy demand. First, modelling is performed with the reference point (controlling the EC transmittance) at the back of the office. Then, an alternative position for the reference point is proposed and the results are compared. Different control strategies for the modulation of the EC transmittance (in response to daylight illuminance) are also investigated (linear and non-linear control, Figure 5-1) with the aim of optimizing the system. It is hoped that models based on useful daylight illuminances might assist in rendering the simulation results more realistic and the proposed energy savings more achievable in practice. Finally, the effect of EC glazing on one aspect of visual comfort is addressed.

5.3.1 Daylight Illuminance with EC Reference Point at the Back - Non-Linear

The same side-lit office model introduced in Section 3.3.1 was used here except that the clear double glazing (transmittance of 0.76) of the window was replaced by EC glazing whose range of visible transmittance was variable from 0.1 to 0.8 (values representing the limits of achievable performance) [Selkowitz et al., 1994][DiBartolomeo et al., 1996]. The control strategy was designed in such a way that the transmittance of the window was varied between the bleached (0.8) and coloured (0.1) states in order to maintain and not exceed a maximum daylight illuminance of 500 lux, whenever possible, at a specific reference point in the office. The reference point, as before, was taken on the workplane at a distance of 4.25 m. from the window (i.e., two thirds the depth of the office). This EC control strategy is termed 'non-linear' control. In order to achieve this, the control strategy was set up as shown in Figure 5-10 and the following equations:

$$\begin{gathered} If(\text{ illuminance at reference point} \leq 500\text{ lux}) \\ Then(\text{ transmittance} = 0.8) \end{gathered}$$

$$If\,(500\text{ lux} < \text{illuminance at reference point} < 4000\text{ lux})$$

$$Then\left(\text{transmittance} = \frac{500\text{ lux} \times 0.8}{\text{illuminance at reference point}}\right)$$

$$If\,(\text{illuminance at reference point} \geq 4000\text{ lux})$$

$$Then\,(\text{transmittance} = 0.1)$$

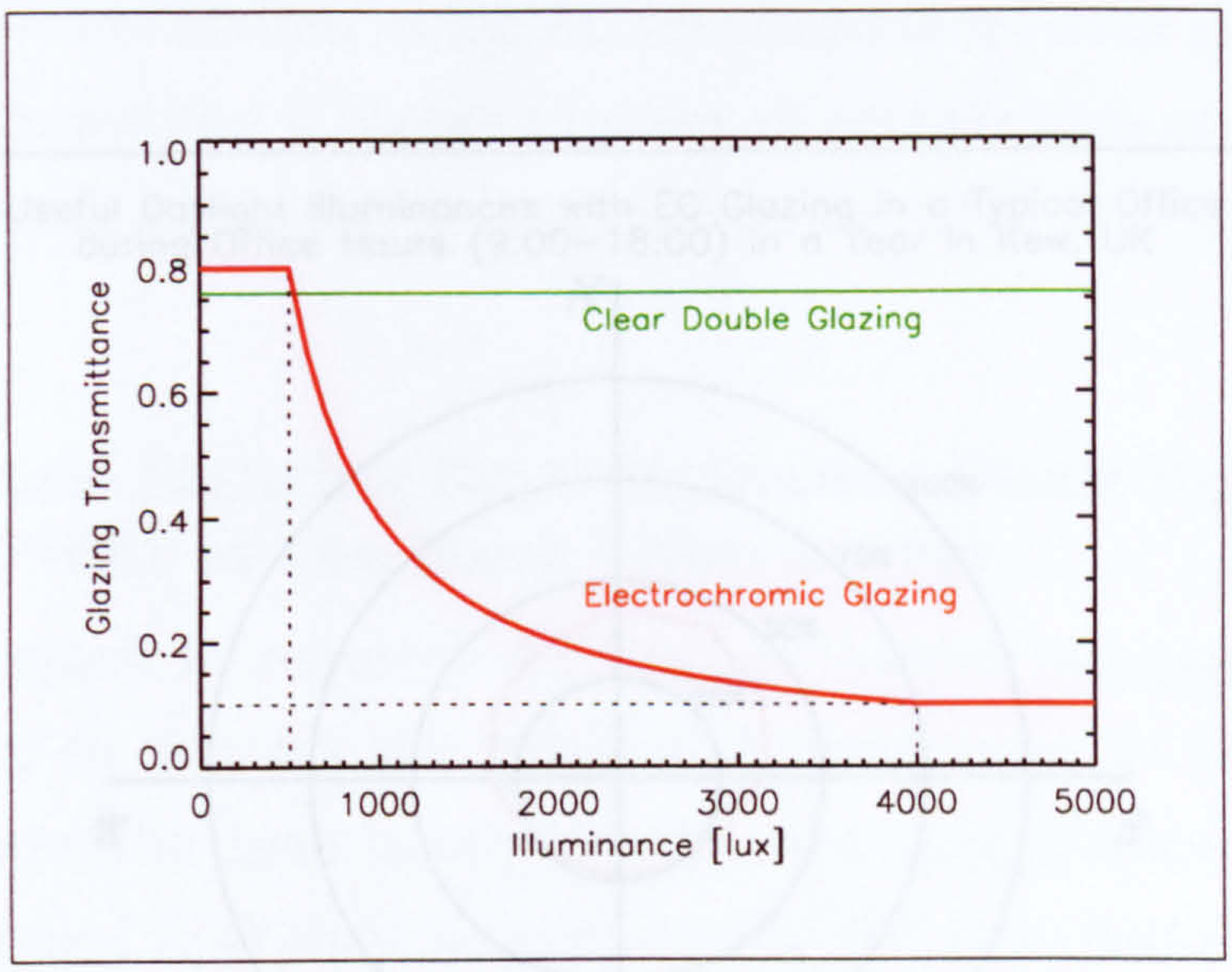

Figure 5-10 EC transmittance 'non-linear' switching in response to daylight illuminance in order to maintain 500 lux at the reference point at the back of the office

The upper limit of 4000 lux was computed as the maximum illuminance that can be reduced to 500 lux by the lowest EC transmittance of 0.1, i.e., $\frac{500\text{ lux} \times 0.8}{0.1}$ = 4000 lux. In other words, when daylight illuminances equal to or lower than 500 lux are detected at the reference point, the EC glazing remains clear at its maximum transmittance of 0.8. For daylight illuminances higher than 500 lux and lower than 4000 lux at the reference point, the EC transmittance is lowered accordingly in order to reduce the illuminance to 500 lux. For example, in response to 1000 lux, the transmittance decreases to 0.4, and for 2000 lux, it becomes 0.2. In response to daylight illuminances equal to or higher than 4000 lux at the reference point, the EC glazing switches to its darkest state with a transmittance of 0.1.

The hourly daylight illuminances already derived for the office model were modulated according to the control strategy in order to mimic the effect of the full range of possible transmittance values for the EC glazing[10]. The resulting internal illuminances were then examined in order to determine how often they were in the useful range. These occurrences were calculated as percentages of the working year by multiplying the numbers of hours by $\frac{100\%}{3650}$. They are shown in Figure 5-11 for 12 azimuth orientations starting

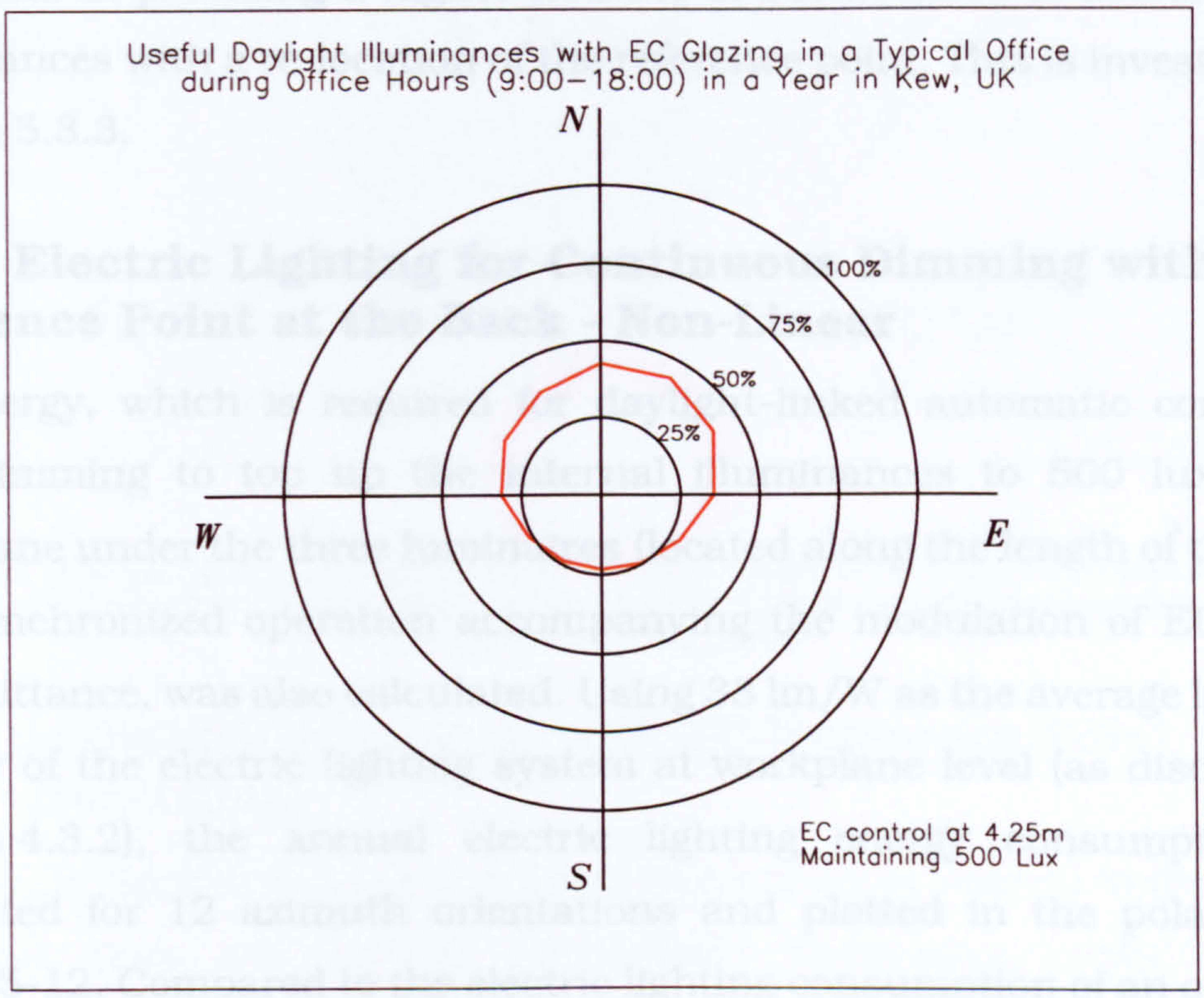

Figure 5-11 Occurrences of useful daylight illuminances with EC glazing of transmittance 0.1 - 0.8, maintaining a maximum of 500 lux at the back of the office

from north and incrementing clockwise by 30° at a time in order to cover a complete 360° azimuth rotation. With useful daylight illuminance occurrences of 23.8% of the working year for south, 35.6% for east, 42.8% for north, and 31.4% for west, this does not constitute much of an

10. Note that, unlike blinds, changes to EC transmittance are homogeneous. Thus, this EC model of transmittance modulation is likely to be more realistic than the simple shutter model for blinds used earlier.

improvement over the useful daylight illuminance results obtained for unshaded clear glazing in Figure 4-6 (17.6%, 36.3%, 43.6%, and 24.6% for south, east, north, and west, respectively). This is not surprising since, as discussed before, maintaining a daylight illuminance of 500 lux at the back of the office means relaxing the transmittance of the EC glazing most of the time and, hence, subjecting the front of the office to much higher illuminances than those which would fall into the useful range. Therefore, this non-linear modulation of the EC transmittance could perhaps be more successful in providing a higher number of occurrences of useful daylight illuminances with a re-location of the reference point. This is investigated in Section 5.3.3.

5.3.2 Electric Lighting for Continuous Dimming with EC Reference Point at the Back - Non-Linear

The energy, which is required for daylight-linked automatic continuous light dimming to top up the internal illuminances to 500 lux on the workplane under the three luminaires (located along the length of the office) in a synchronized operation accompanying the modulation of EC glazing transmittance, was also calculated. Using 33 lm/W as the average luminous efficacy of the electric lighting system at workplane level (as discussed in Section 4.3.2), the annual electric lighting energy consumption was calculated for 12 azimuth orientations and plotted in the polar plot of Figure 5-12. Compared to the electric lighting consumption of an office with continuous light dimming and an unshaded clear-glazed window (in Figure 4-9), there is only a slight increase in electric lighting consumption with EC glazing, particularly for the southern and western orientations. This is not surprising since the status of the internal daylight illuminance due to the clear and the EC windows appear not to differ much (i.e., occurrences of useful daylight illuminances with unshaded clear glazing in Figure 4-6 and those with EC glazing in Figure 5-11 look very similar).

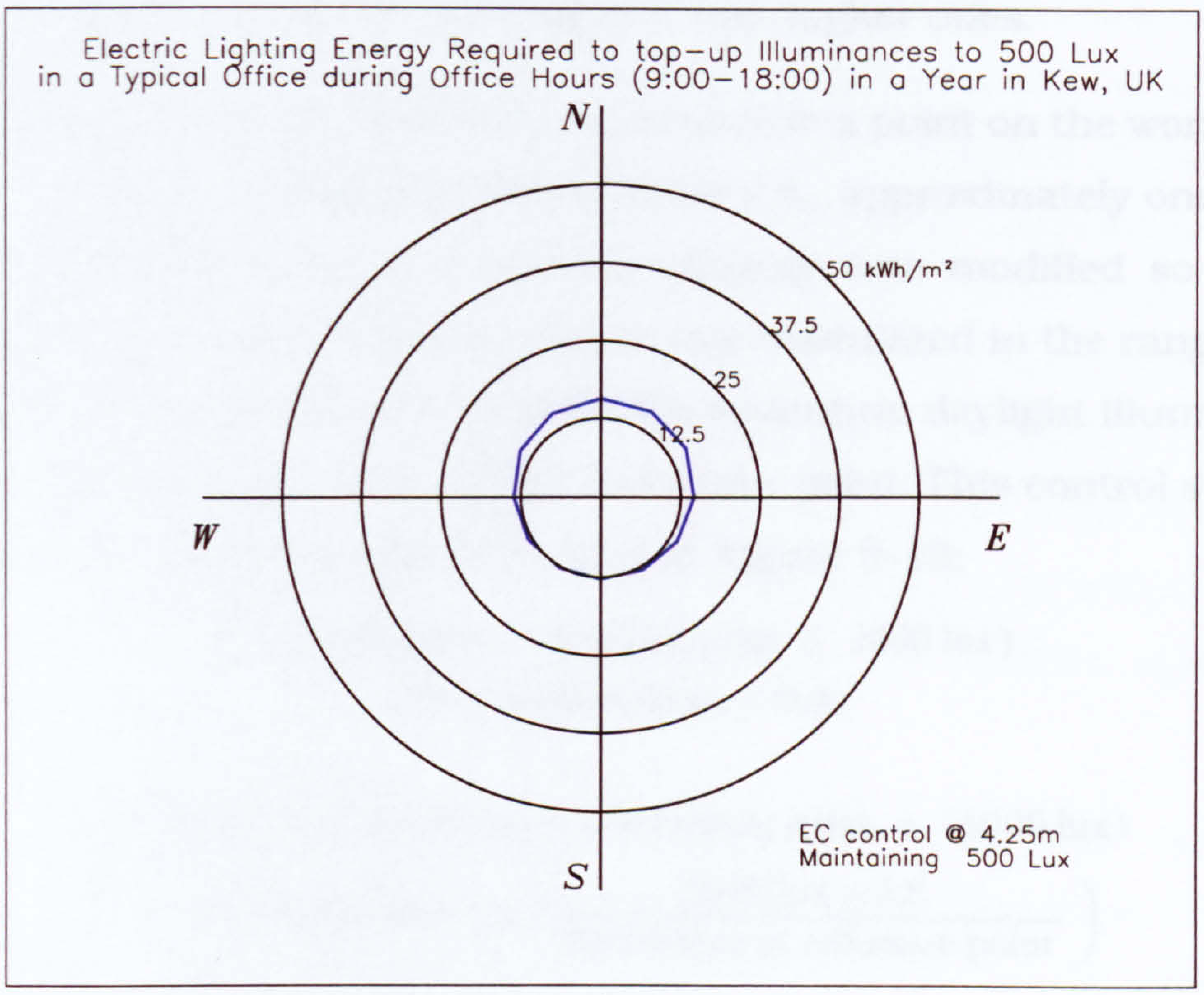

Figure 5-12 Annual lighting energy demand for continuous dimming control with non-linear switching of EC transmittance between 0.1 and 0.8 in order to maintain a maximum of 500 lux at the back of the office

5.3.3 Daylight Illuminance with EC Reference Point at the Front - Non-Linear

As shown in Section 5.3.1, referencing EC non-linear control to the back of the office does not provide particularly impressive useful daylight illuminance results. Hence, an alternative position for the reference point is proposed below.

Since the front of the office, i.e, closest to the window, is the place where occupants are most likely to experience the very high daylight illuminances which can potentially cause discomfort, it seems reasonable to set the reference point for any strategy controlling the modulation of the admitted daylight illuminance at the front of the office. Following the introduced concept of useful daylight illuminances, i.e., considering illuminances from 100 to 2000 lux as useful and desirable, it also makes sense that 2000 lux would be the illuminance value to try and maintain (and not exceed) at the front of the office, while 'dampening out' any higher ones.

The reference point was, therefore, re-located to a point on the workplane at a distance of just 1.25 m. from the window (i.e., approximately one fifth the depth of the office), and the control strategy was modified so that the transmittance of the EC-glazed window was modulated in the range of 0.1 - 0.8 in order to maintain and not exceed a maximum daylight illuminance of 2000 lux, whenever possible, at this reference point. This control strategy is detailed in the following equations and in Figure 5-13:

$$\begin{gathered} If(\text{ illuminance at reference point } \leq 2000 \text{ lux}) \\ Then(\text{ transmittance} = 0.8) \end{gathered}$$

$$\begin{gathered} If(\text{ 2000 lux} < \text{illuminance at reference point } < 16000 \text{ lux}) \\ Then\left(\text{ transmittance} = \frac{2000 \text{ lux} \times 0.8}{\text{illuminance at reference point}}\right) \end{gathered}$$

$$\begin{gathered} If(\text{ illuminance at reference point } \geq 16000 \text{ lux}) \\ Then(\text{ transmittance} = 0.1) \end{gathered}$$

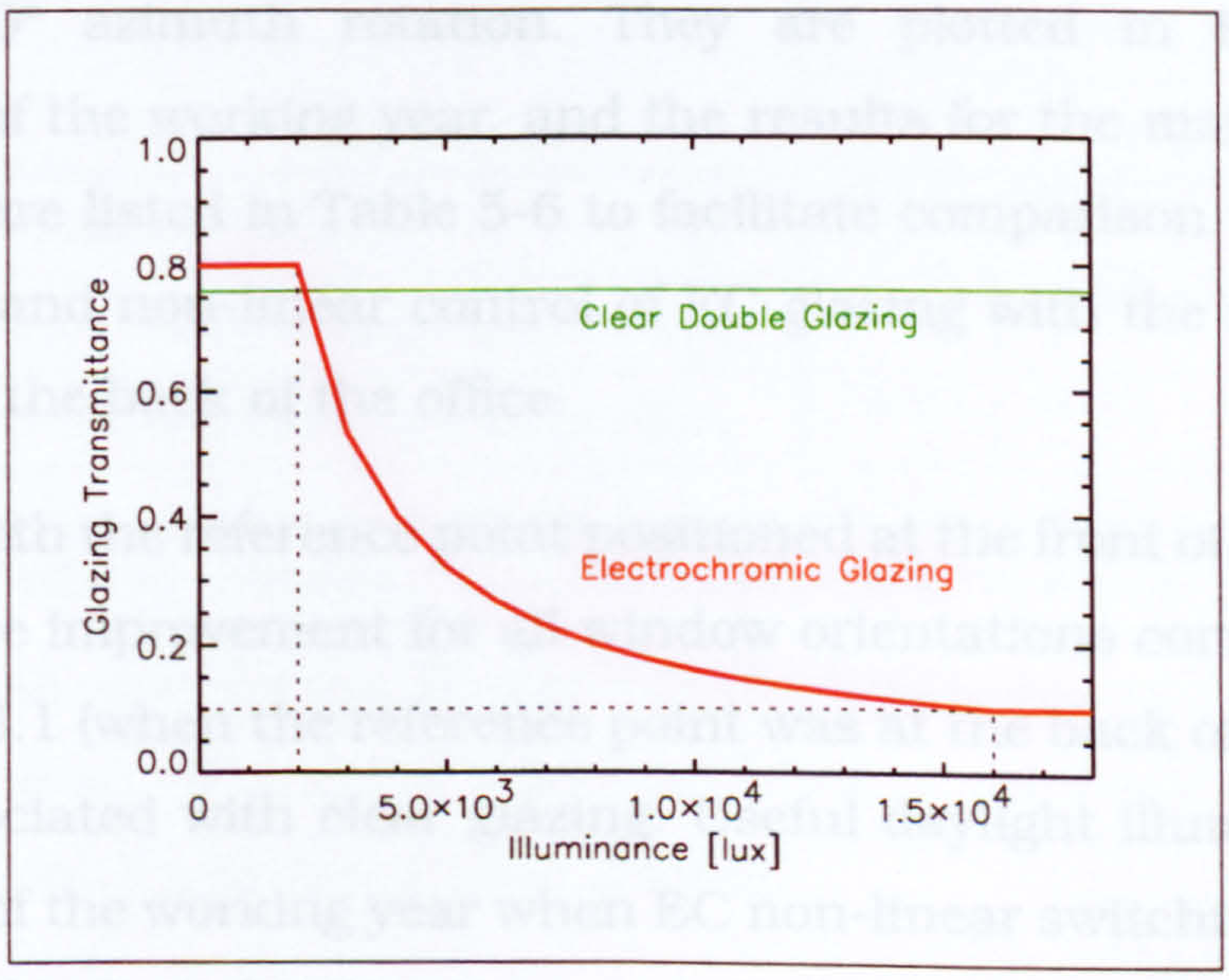

Figure 5-13 EC transmittance non-linear switching in response to illuminance in order to maintain 2000 lux at the reference point at the front of the office

The upper limit of 16000 lux was computed as the maximum daylight illuminance that can be reduced to 2000 lux by the lowest EC transmittance of 0.1, i.e., $\frac{2000 \text{ lux} \times 0.8}{0.1}$ = 16000 lux. In other words, when daylight illuminances equal to or lower than 2000 lux are detected at the reference point, the EC glazing remains clear at its maximum transmittance of 0.8. For daylight illuminances higher than 2000 lux and lower than 16000 lux at the reference point, the EC transmittance is lowered accordingly in order to reduce the illuminance to 2000 lux. For example, in response to 4000 lux, the transmittance decreases to 0.4, and for 8000 lux, it becomes 0.2. In response to daylight illuminances equal to or higher than 16000 lux at the reference point, the EC glazing switches to its darkest state with a transmittance of 0.1.

The hourly daylight illuminances derived for the office model were modulated according to the control strategy in order to mimic the effect of the full range of possible transmittance values for the EC glazing. The occurrences of useful daylight illuminances resulting from this modified control strategy were calculated for 12 azimuth orientations starting from north and incrementing clockwise by 30° at a time in order to cover a complete 360° azimuth rotation. They are plotted in Figure 5-14 as percentages of the working year, and the results for the main four window orientations are listed in Table 5-6 to facilitate comparison with unshaded clear glazing and non-linear control of EC glazing with the reference point positioned at the back of the office.

The results with the reference point positioned at the front of the office show a considerable improvement for all window orientations compared to those in Section 5.3.1 (when the reference point was at the back of the office) and to those associated with clear glazing. Useful daylight illuminances occur during most of the working year when EC non-linear switching is controlled according to the daylight illuminance at the front of the office. For example, for a window facing due north, east, south, and west, they occur 77.4%, 76.3%, 68%, and 68.1% of the working year, respectively. For all window

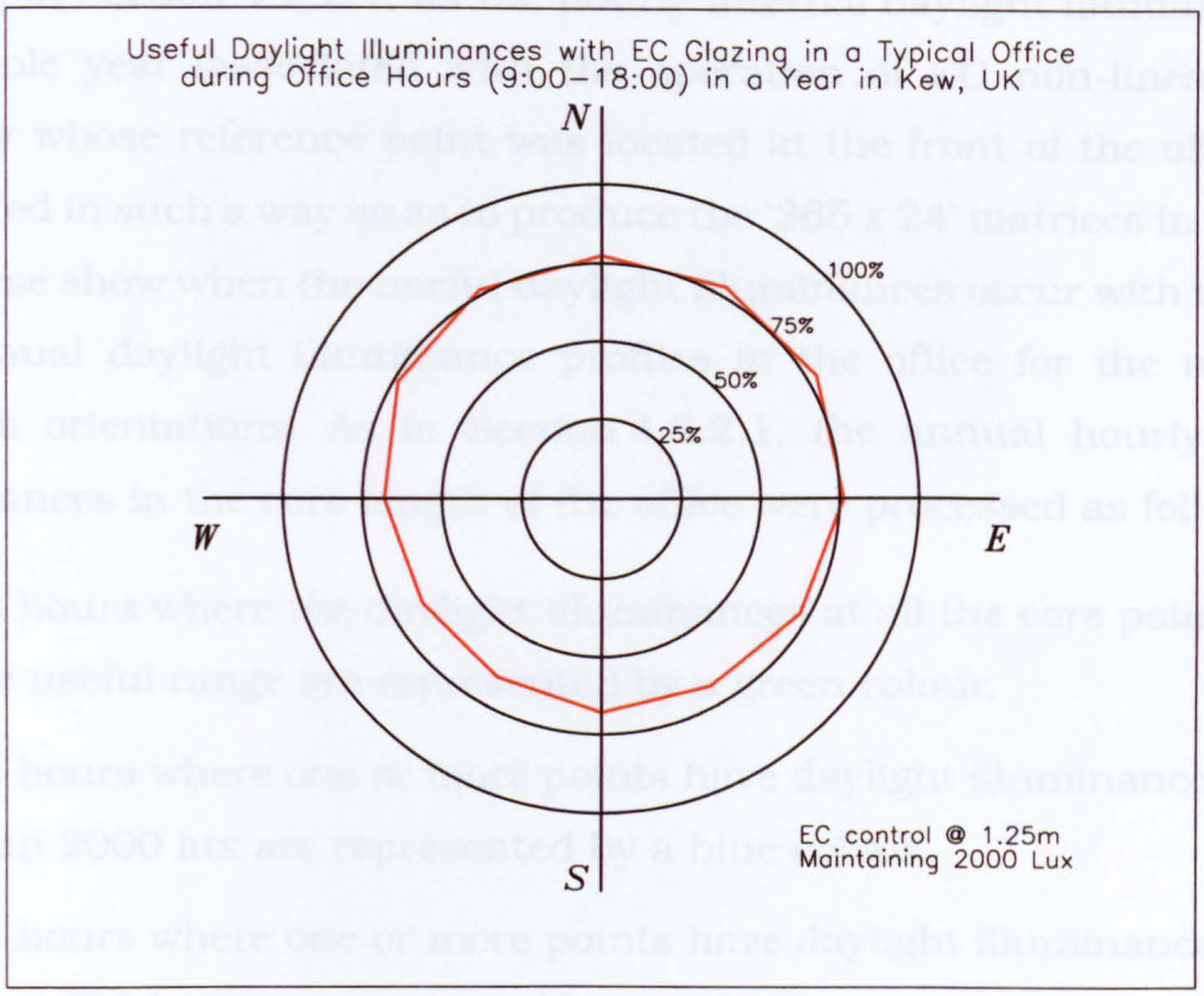

Figure 5-14 Occurrences of useful daylight illuminances with non-linear switching of EC transmittance between 0.1 and 0.8 in order to maintain a maximum of 2000 lux at the front of the office

Type of Glazing	Percentage of Working Year			
	North	East	South	West
Unshaded clear glazing (T=0.76)	43.6%	36.3%	17.6%	24.6%
EC non-linear control referenced to back of office	42.8%	35.6%	23.4%	31.4%
EC non-linear control referenced to front of office	77.4%	76.3%	68.0%	68.1%

Table 5-6 Occurrences of useful daylight illuminances with EC glazing of transmittance 0.1 - 0.8, controlled by a reference point at the back and at the front of the office

orientations, the occurrences of useful daylight illuminances are more than double those obtained with the reference point at the back of the office or those obtained with unshaded clear glazing.

5.3.3.1 Visualization of Annual Daylight Illuminance Profiles

In addition to calculating the improved occurring frequency of useful daylight illuminances as a percentage of the working year, it is instructive to also know when the improvements occur. Therefore, similar to the process in Section 4.2.2.1, all the hourly internal daylight illuminances for the whole year (associated with the operation of EC non-linear control strategy whose reference point was located at the front of the office) were formatted in such a way so as to produce the '365 x 24' matrices in Figure 5-15. These show when the useful daylight illuminances occur with respect to the annual daylight illuminance profiles in the office for the main four azimuth orientations. As in Section 4.2.2.1, the annual hourly daylight illuminances in the core length of the office were processed as follows:

- All hours where the daylight illuminances at all the core points are in the useful range are represented by a green colour.
- All hours where one or more points have daylight illuminances higher than 2000 lux are represented by a blue colour.
- All hours where one or more points have daylight illuminances lower than 100 lux are represented by a red colour.
- All darkness hours (i.e., of zero illuminance) are represented by a grey colour.

Note that, as before, there are no occurrences of hours where one or more points in the core length of the office have daylight illuminances lower than 100 lux while at the same time one or more points have daylight illuminances higher than 2000 lux.

Compared to the profiles due to unshaded clear glazing (Figure 4-7), there are distinct improvements with an EC window with non-linear control referenced to the front of the office. For example, for an EC window facing due south (with useful daylight illuminances occurring 68% of the time during office hours), apart from few sporadic occurrences of daylight illuminances higher than 2000 lux, these exceptionally high daylight illuminances are mainly concentrated between 10:00 a.m. and 2:00 p.m. in March and April and from August until October. An additional form of shading (for example, blinds) may be required during those times. For an

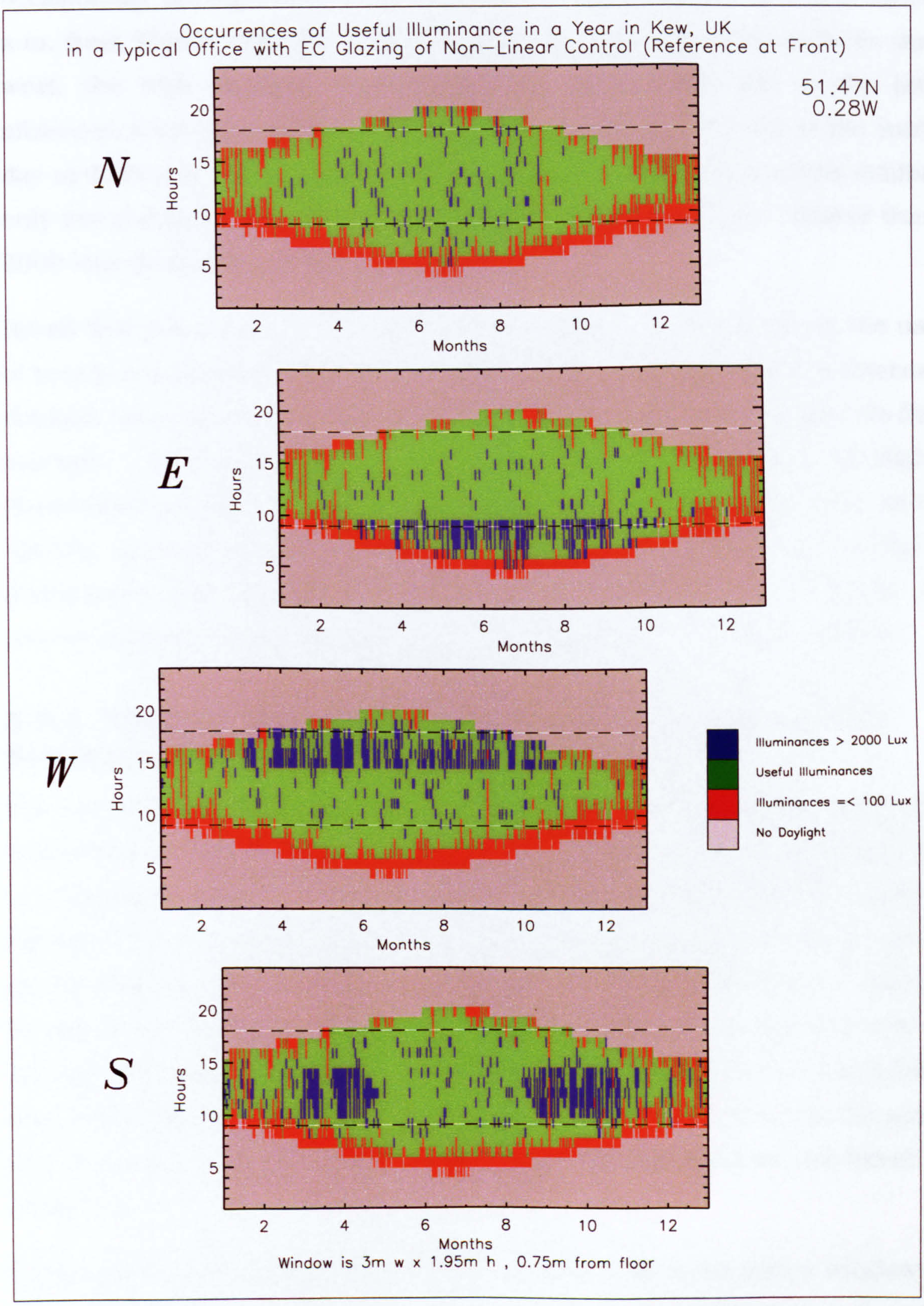

Figure 5-15 Useful daylight illuminances annual profiles with EC glazing of transmittance 0.1 - 0.8, maintaining a maximum of 2000 lux at the front of the office

eastern orientation of the EC window, high daylight illuminances occur occasionally during office hours but particularly between 9:00 and 10:00 a.m. from March until the end of September. If the EC window faces due west, the high daylight illuminances will be concentrated in the late afternoon from approximately 3:00 p.m. until almost the end of the work day at 6:00 p.m.. On the other hand, a northern orientation would exhibit only few isolated hours of very high daylight illuminances (i.e., higher than 2000 lux) during the whole working year.

Recall that the occurrences denoted in the figure are hourly due to the use of hourly irradiation data (from the climate file) in the derivation of internal daylight illuminances (Chapter 3). Using a shorter time-step climate file (for example, half-hourly or quarter-hourly) would result in daylight illuminance profiles of a higher frequency, thus providing an even more specific description of the short-step changes in the internal daylight illuminance characteristics due to the performance of ECs. This is, of course, also applicable for studying other dynamic fenestration devices.

5.3.4 Electric Lighting for Continuous Dimming with EC Reference Point at the Front - Non-Linear

The non-linear control of EC glazing transmittance (with the reference point positioned at the front of the office) was simulated as accompanied by synchronized daylight-linked automatic continuous dimming of the electric lighting. The annual lighting energy required for continuous dimming to top up the illuminance to 500 lux was calculated, considering separate control for the three luminaires along the length of the office and using 33 lm/W as the average luminous efficacy of the electric lighting system at workplane level. This was computed for 12 azimuth orientations as shown in the polar plot of Figure 5-16 and results for the main four orientations are listed in Table 5-7.

Compared to the lighting energy requirements associated with a window of unshaded clear glazing (in Figure 4-9 and Table 4-4), at first glance, it might

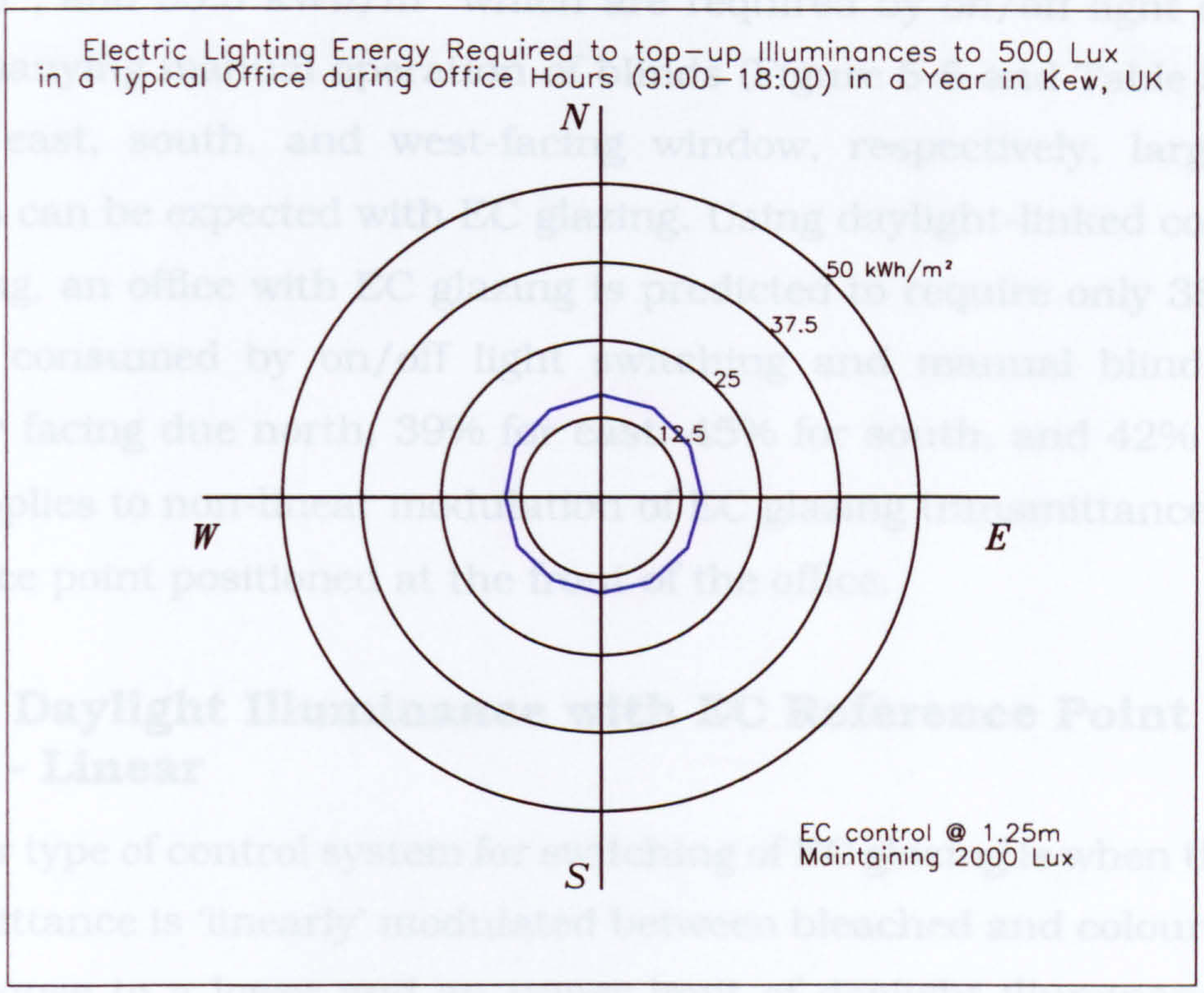

Figure 5-16 Annual lighting energy demand for continuous dimming control with non-linear switching of EC transmittance between 0.1 and 0.8 in order to maintain a maximum of 2000 lux at the front of the office

Type of Glazing	kWh/m²			
	North	East	South	West
EC non-linear control referenced to back of office	15.7	14.6	12.8	13.6
EC non-linear control referenced to front of office	16.2	15.8	15.1	14.9

Table 5-7 Artificial lighting energy demand in kWh/m² for continuous dimming with EC glazing of transmittance 0.1 - 0.8, controlled by a reference point at the back and at the front of the office

be conceived that EC does not offer any energy savings. Recall, however, that (as discussed earlier) an unshaded clear window is, in fact, not practical and that energy calculations based on unshaded windows are usually unachievable in practice. Therefore, it would be more realistic to compare the energy consumption of an advanced system such as an EC window with continuous light dimming to the energy consumed by the typical system of manually operated blinds and on/off light switching discussed in Section 5.1.3. Compared to 42.5 kWh/m^2, 40.5 kWh/m^2, 33.8 kWh/m^2, and 35.5 kWh/m^2 which are required by on/off light switching accompanying manual operation of blinds (Figure 5-5 and Table 5-2) for a north, east, south, and west-facing window, respectively, large energy savings can be expected with EC glazing. Using daylight-linked continuous dimming, an office with EC glazing is predicted to require only 38% of the energy consumed by on/off light switching and manual blinds with a window facing due north, 39% for east, 45% for south, and 42% for west. This applies to non-linear modulation of EC glazing transmittance with the reference point positioned at the front of the office.

5.3.5 Daylight Illuminance with EC Reference Point at the Front - Linear

Another type of control system for switching of EC glazing is when the visible transmittance is 'linearly' modulated between bleached and coloured states in response to a lower and an upper limit of daylight illuminance at the reference point. The reference point was positioned at the front of the office (at a distance of 1.25 m. from the window). If the value of daylight illuminance at which the EC glazing is bleached is taken to be 2000 lux, a test is needed to determine the level of daylight illuminance at which the EC glazing should be at its darkest to achieve the strategy objectives. Hence, an optimization test was carried out in which 16 values of threshold daylight illuminance were tested. They ranged from 2250 lux to 6000 lux, incrementing by 250 lux (i.e., 2250 lux, 2500 lux, 2750 lux,.... until 6000 lux), while the transmittance of the window was modulated in the range of 0.1 - 0.8. The percentage of the working year when useful daylight illuminances occur was calculated for each test value and for 12 azimuth orientations starting from north and incrementing clockwise by 30° at a time in order to cover a complete 360° azimuth rotation[11]. They are plotted in Figure 5-17.

As shown in the figure, for all window orientations, a maximum daylight illuminance of 3750 lux at the front of the office would result in the

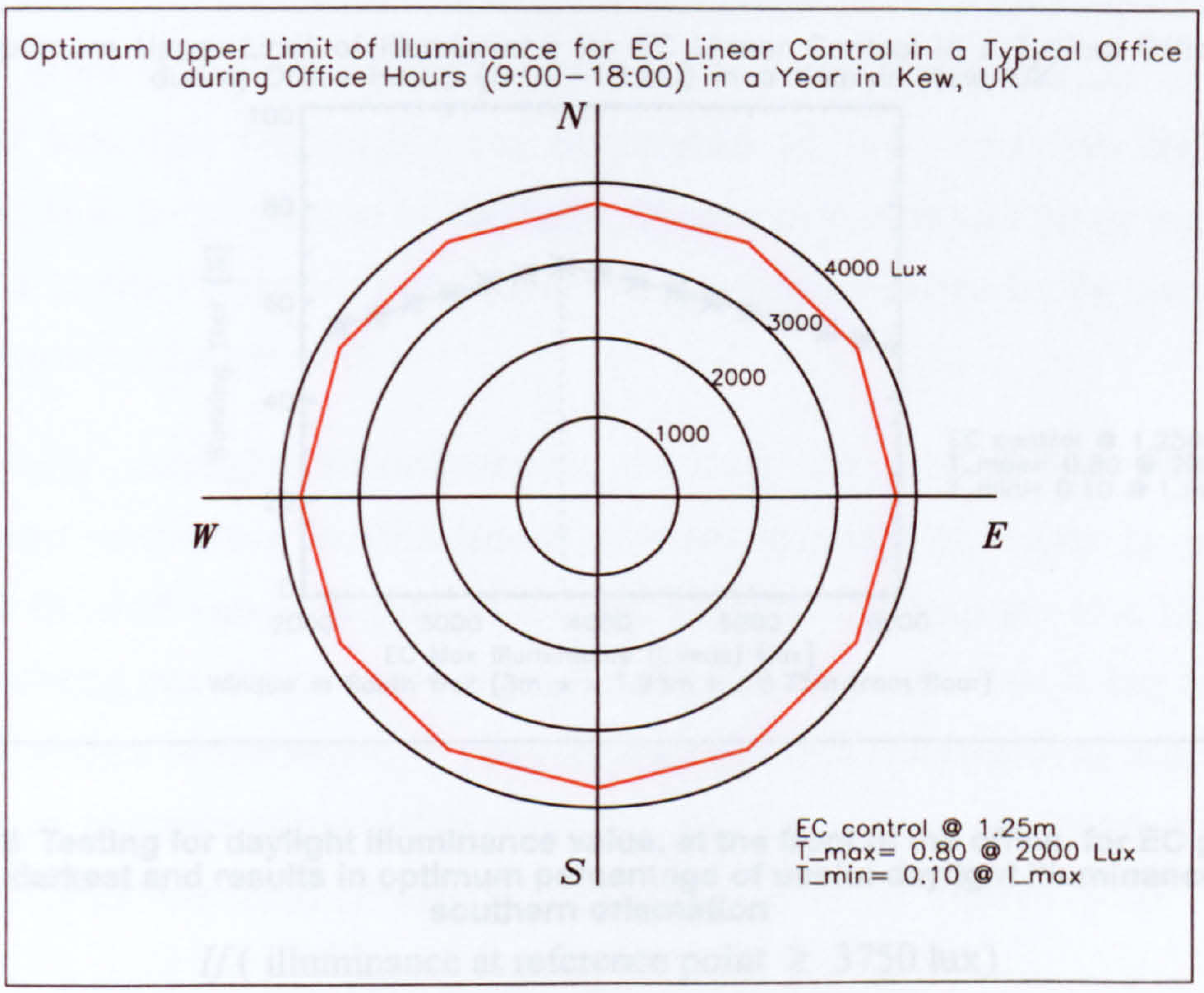

Figure 5-17 Testing for daylight illuminance value, at the front of the office, for EC glazing to be at its darkest and results in optimum percentage of useful daylight illuminances

maximum occurrences of useful daylight illuminances. In fact, running that optimization test for a single window orientation, for example south, the peak of useful daylight illuminance occurrences was clear at 3750 lux with a value of 67.4% of the working year, as shown in Figure 5-18. Therefore, the linear control strategy for EC modulation was set as shown in the following equations and in Figure 5-19:

$$If(\text{ illuminance at reference point } \leq 2000 \text{ lux})$$
$$Then(\text{ transmittance} = 0.8)$$

$$If(\text{ } 2000 \text{ lux} < \text{illuminance at reference point } < 3750 \text{ lux})$$

$$Then \text{ transmittance} = \left(\left(\frac{0.1 - 0.8}{3750 - 2000}\right) \times (\text{ illuminance at reference point } - 2000)\right) + 0.8$$

11. Note that for these optimization tests, several million (over 9.9 in this case) internal illuminance values were derived and processed using new XDAPS procedures written by the author.

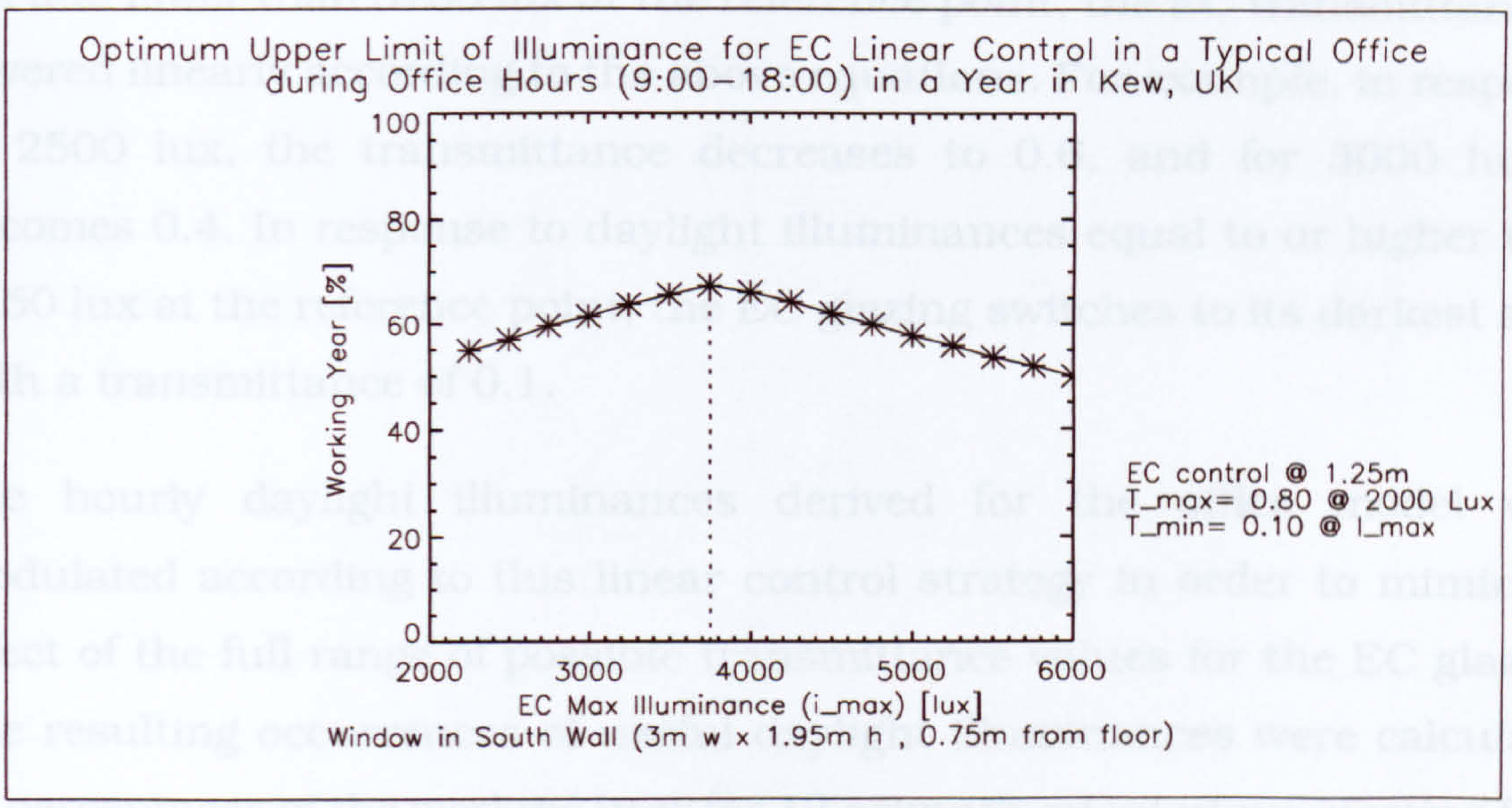

Figure 5-18 Testing for daylight illuminance value, at the front of the office, for EC glazing to be at its darkest and results in optimum percentage of useful daylight illuminances, for a southern orientation

$$If(\text{ illuminance at reference point } \geq 3750 \text{ lux})$$
$$Then(\text{ transmittance} = 0.1)$$

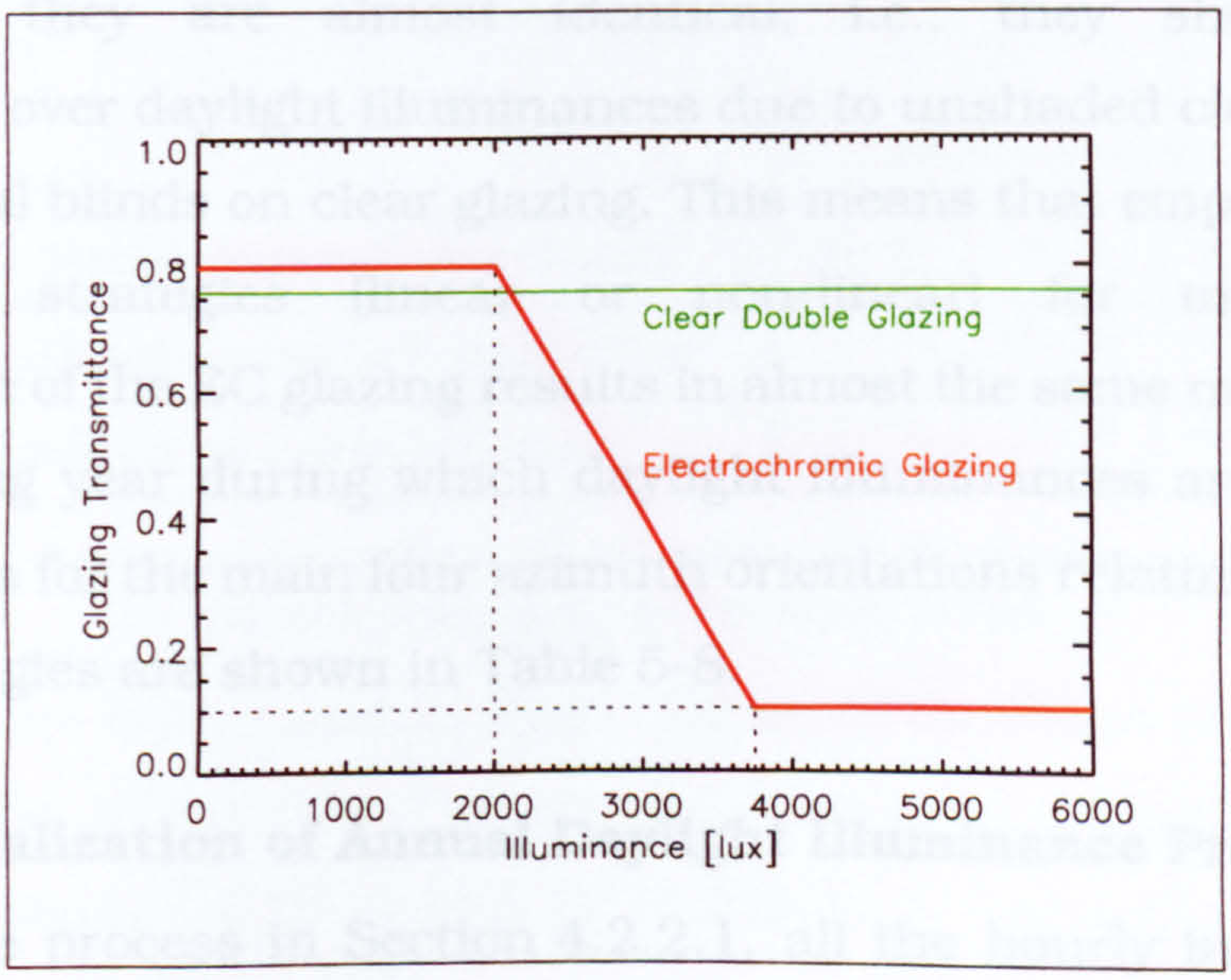

Figure 5-19 EC transmittance 'linear' switching from 0.8 to 0.1 in response to illuminance of 2000 lux to 3750 lux at the reference point at the front of the office

In other words, when daylight illuminances equal to or lower than 2000 lux are detected at the reference point, the EC glazing remains clear at its maximum transmittance of 0.8. For daylight illuminances higher than 2000 lux and lower than 3750 lux at the reference point, the EC transmittance is lowered linearly according to the above equations. For example, in response to 2500 lux, the transmittance decreases to 0.6, and for 3000 lux, it becomes 0.4. In response to daylight illuminances equal to or higher than 3750 lux at the reference point, the EC glazing switches to its darkest state with a transmittance of 0.1.

The hourly daylight illuminances derived for the office model were modulated according to this linear control strategy in order to mimic the effect of the full range of possible transmittance values for the EC glazing. The resulting occurrences of useful daylight illuminances were calculated as percentages of the working year for 12 azimuth orientations starting from north and incrementing clockwise by 30° at a time in order to cover a complete 360° azimuth rotation. They are plotted in Figure 5-20.

Comparing these results with the occurrences of useful daylight illuminances due to non-linear EC transmittance switching presented in Figure 5-14, they are almost identical, i.e., they show the same improvement over daylight illuminances due to unshaded clear glazing and due to manual blinds on clear glazing. This means that employing either of the control strategies (linear or non-linear) for modulating the transmittance of the EC glazing results in almost the same number of hours in the working year during which daylight illuminances are in the useful range. Results for the main four azimuth orientations relating to the two EC control strategies are shown in Table 5-8.

5.3.5.1 Visualization of Annual Daylight Illuminance Profiles

Similar to the process in Section 4.2.2.1, all the hourly internal daylight illuminances for the whole year associated with the operation of EC linear control strategy were processed in such a way so as to produce the '365 x 24' matrices in Figure 5-21. These profiles demonstrate when useful daylight illuminances occur with respect to the annual illuminance profiles

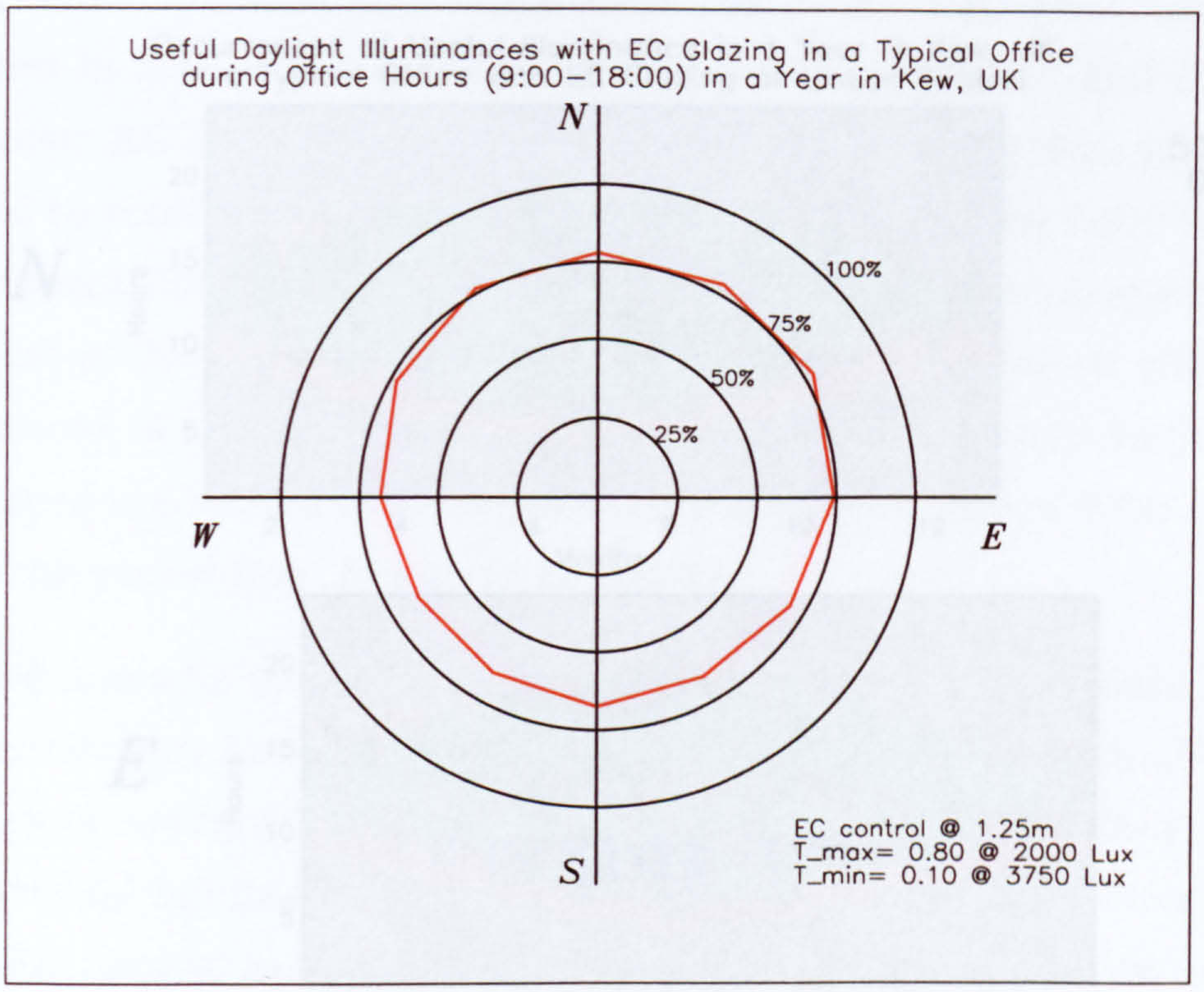

Figure 5-20 Occurrences of useful daylight illuminances with linear switching of EC transmittance from 0.8 to 0.1 in response to illuminance of 2000 lux to 3750 lux at the front of the office

Type of EC Glazing Transmittance Control	Percentage of Working Year			
	North	East	South	West
Non-linear control referenced to front of office	77.4%	76.3%	68.0%	68.1%
Linear control referenced to front of office	78.1%	74.2%	67.4%	68.3%

Table 5-8 Occurrences of useful daylight illuminances with EC glazing of transmittance 0.1 - 0.8, with linear and non-linear switching

in the office. The colour coding in the figure is the same as that used for Figure 5-15 and Figure 4-7. The results were then compared with those produced for unshaded clear glazing in Figure 4-7 and for EC non-linear control in Figure 5-15.

Much better performance was observed for linear EC control than with non-linear control, with all the sporadic instances of inconveniently high daylight illuminances, which were noted in Figure 5-15, now non-existent.

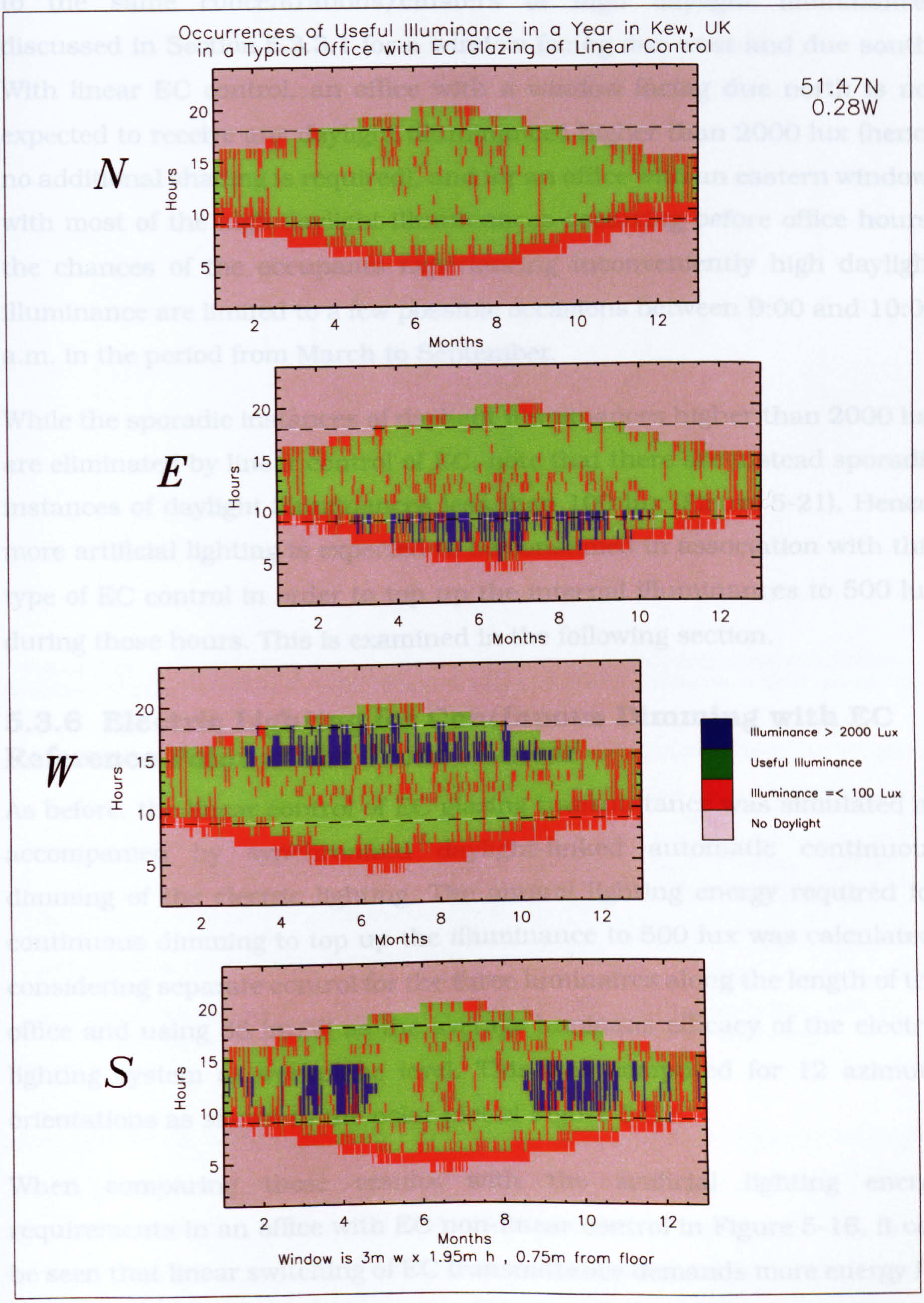

Figure 5-21 Useful daylight illuminances annual profiles with EC glazing of transmittance from 0.8 to 0.1 in response to illuminance of 2000 lux to 3750 lux at the front of the office

Any need for additional shading with linear control of EC glazing is limited to the same concentrations/clusters of high daylight illuminances discussed in Section 5.3.3.1 for a window facing due west and due south. With linear EC control, an office with a window facing due north is not expected to receive any daylight illuminances higher than 2000 lux (hence no additional shading is required), and for an office with an eastern window, with most of the high daylight illuminances occurring before office hours, the chances of the occupants experiencing inconveniently high daylight illuminance are limited to a few possible occasions between 9:00 and 10:00 a.m. in the period from March to September.

While the sporadic instances of daylight illuminances higher than 2000 lux are eliminated by linear control of EC, note that there are instead sporadic instances of daylight illuminances less than 100 lux (Figure 5-21). Hence, more artificial lighting is expected to be consumed in association with this type of EC control in order to top up the internal illuminances to 500 lux during those hours. This is examined in the following section.

5.3.6 Electric Lighting for Continuous Dimming with EC Reference Point at the Front - Linear

As before, the linear control of EC glazing transmittance was simulated as accompanied by synchronized daylight-linked automatic continuous dimming of the electric lighting. The annual lighting energy required for continuous dimming to top up the illuminance to 500 lux was calculated, considering separate control for the three luminaires along the length of the office and using 33 lm/W as the average luminous efficacy of the electric lighting system at workplane level. This was computed for 12 azimuth orientations as shown in the polar plot of Figure 5-22.

When comparing these results with the artificial lighting energy requirements in an office with EC non-linear control in Figure 5-16, it can be seen that linear switching of EC transmittance demands more energy for electric lighting than non-linear switching. As shown for the main four

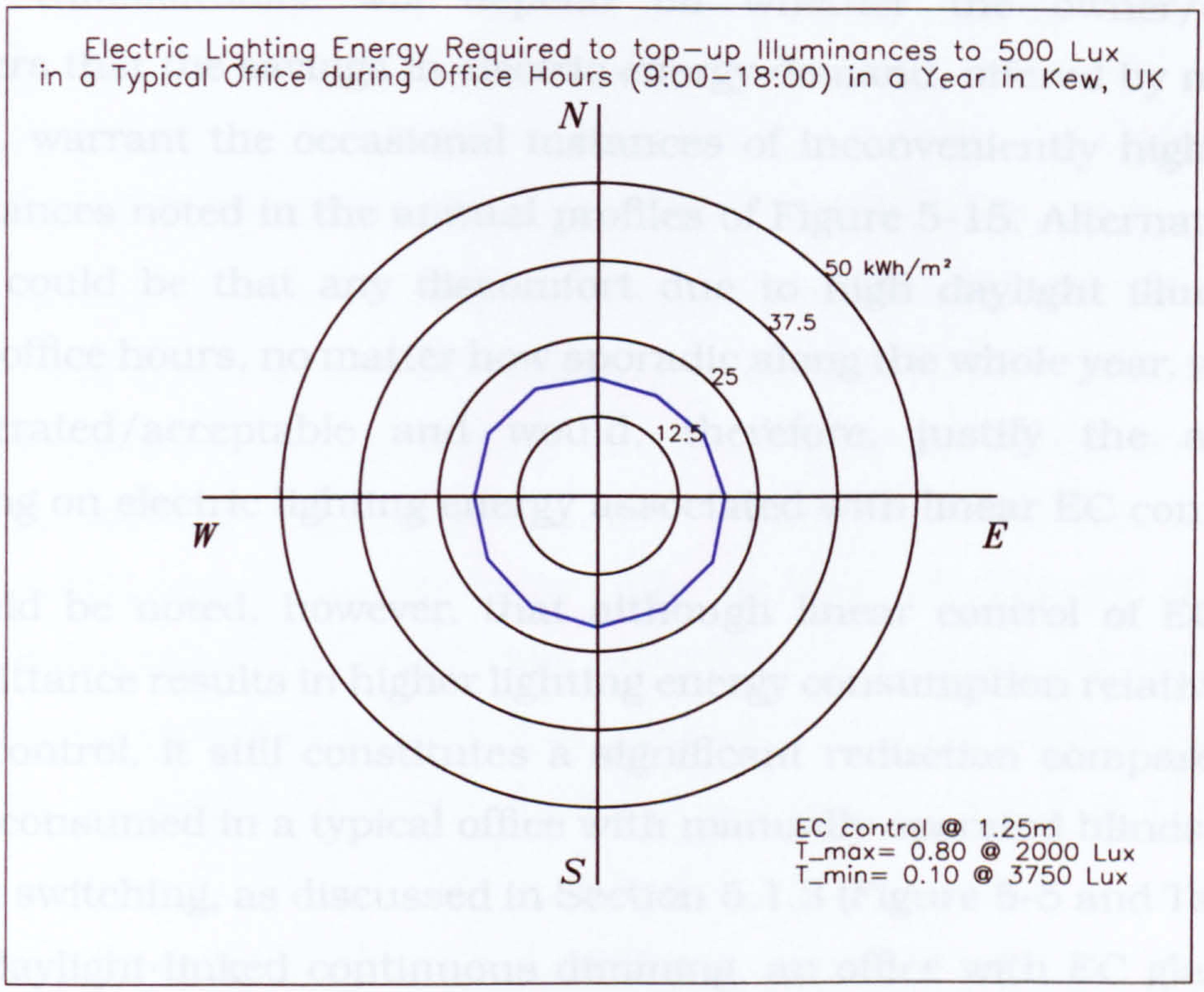

Figure 5-22 Annual lighting energy demand for continuous dimming control with linear switching of EC transmittance from 0.8 to 0.1 in response to illuminance of 2000 lux to 3750 lux at the front of the office

azimuth orientations in Table 5-9, the increase is highest when the window

	kWh/m^2			
Type of EC Glazing Transmittance Control	**North**	**East**	**South**	**West**
Non-linear control referenced to front of office	16.2	15.8	15.1	14.9
Linear control referenced to front of office	18.5	19.8	21.1	19.4

Table 5-9 Artificial lighting energy demand in kWh/m^2 for continuous dimming with EC glazing of transmittance 0.1 - 0.8, with linear and non-linear switching

faces due south with 40% more electric energy required for light dimming if the EC glazing has linear control rather than non-linear control (21.1 kWh/m^2 instead of 15.1 kWh/m^2), and the increase is lowest at 14% for a northern window orientation (18.5 kWh/m^2 instead of 16.2 kWh/m^2).

Considering all the above, the choice of a control system for switching of EC glazing transmittance will depend on whether the owner/developer considers that the savings in electric energy demand, offered by non-linear control, warrant the occasional instances of inconveniently high daylight illuminances noted in the annual profiles of Figure 5-15. Alternatively, the choice could be that any discomfort due to high daylight illuminances during office hours, no matter how sporadic along the whole year, would not be tolerated/acceptable and would, therefore, justify the additional spending on electric lighting energy associated with linear EC control.

It should be noted, however, that although linear control of EC glazing transmittance results in higher lighting energy consumption relative to non-linear control, it still constitutes a significant reduction compared to the energy consumed in a typical office with manually operated blinds and on/off light switching, as discussed in Section 5.1.3 (Figure 5-5 and Table 5-2). Using daylight-linked continuous dimming, an office with EC glazing and linear control is predicted to require only 43% of the energy consumed by on/off light switching and manual blinds (on clear glazing) with a window facing due north, 49% for east, 62% for south, and 55% for west.

In addition, it has been argued that even when lighting energy savings were not obtainable while using EC windows, the visual environment produced by the EC windows, indicated by well-controlled internal illuminance levels, can be significantly improved for computer-type tasks throughout the day compared to the visual environment with conventional clear glazing [Lee et al., 2000a]. This issue is investigated in the next section on glare subjective rating and visual comfort. Also, as discussed before, it has been argued that lighting of work spaces is more than just illuminating a visual task and running cost-benefit analyses of the artificial lighting installation. It is suggested that it also has to do with the comfort levels in the workplace, productivity and the absenteeism of the workers, energy consumption of heating and air-conditioning, as well as lighting, and the possible impact on the environment [Sweitzer, 1991]. As such, finding an optimum balance between daylight, artificial lighting, and the energy consumption of a building (through trade-offs between economic, energy and human perception factors) is considered a very complex issue.

5.3.7 Glare Subjective Rating with EC Glazing

As discussed in Section 4.4.2, the question of visual comfort, with respect to daylighting systems and advanced fenestration devices, is tackled in this study using glare subjective rating, which is a measure of discomfort glare caused by viewing high or non-uniform luminance for visual display terminal (VDT) tasks. In order to quantify the effect of using EC glazing on visual comfort inside the office with regards to VDT tasks, the distribution of the glare subjective rating, *SR*, was calculated with the office model facing due south, as shown in Figure 5-23 for non-linear control of EC glazing

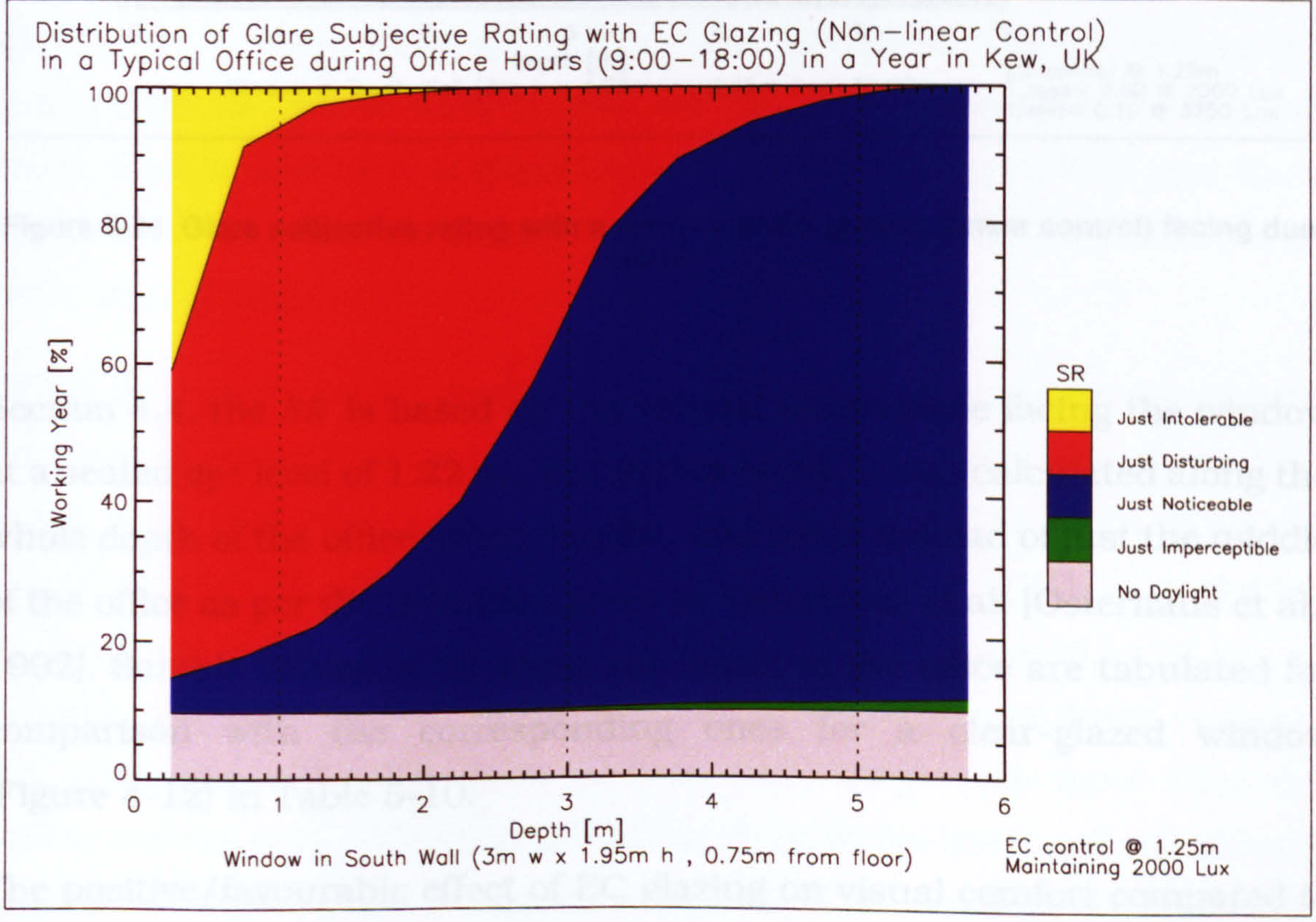

Figure 5-23 Glare subjective rating with a window of EC glazing (whose transmittance is modulated using non-linear control) facing due south

transmittance and in Figure 5-24 for linear control. As detailed in

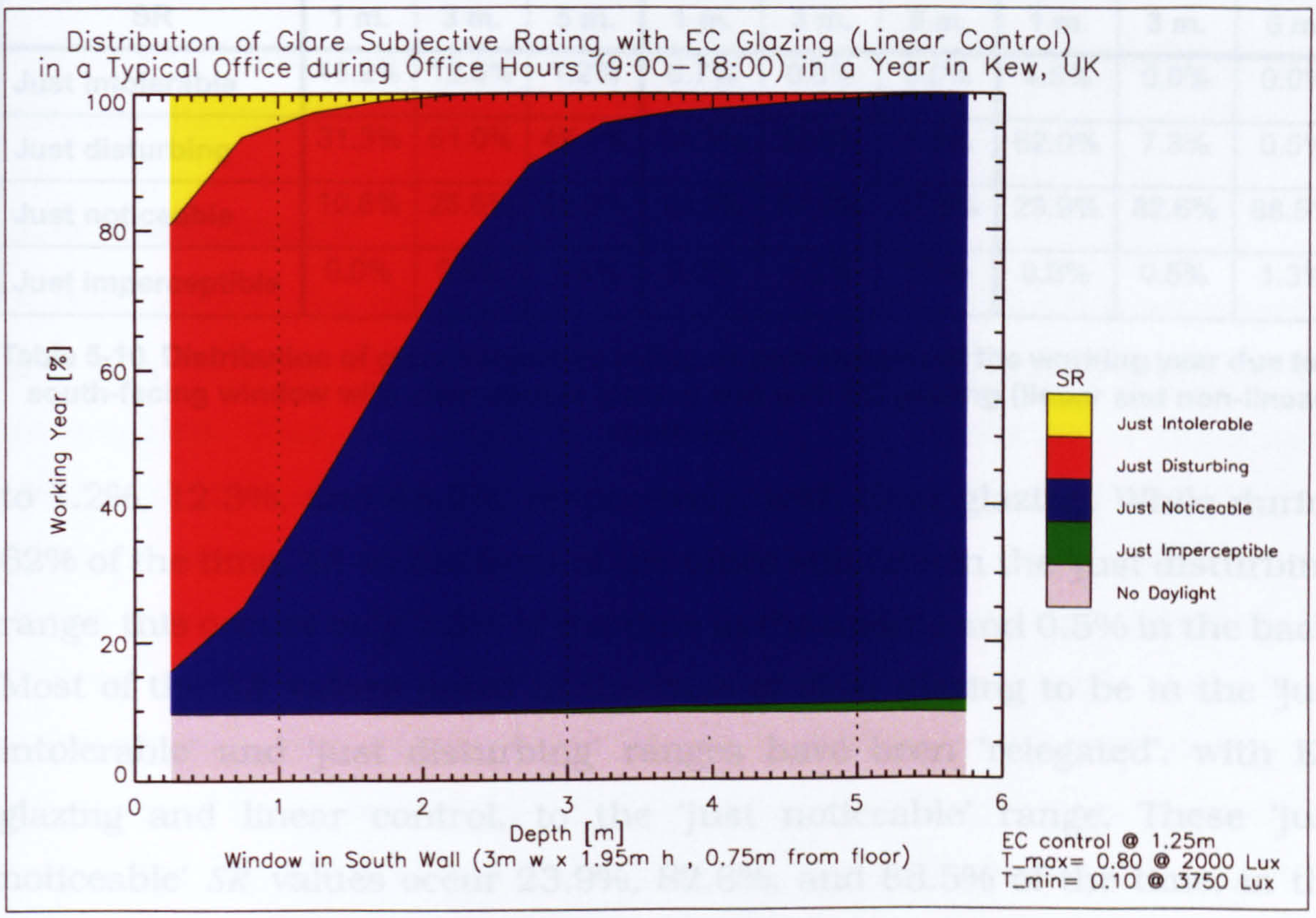

Figure 5-24 Glare subjective rating with a window of EC glazing (linear control) facing due south

Section 4.4, the *SR* is based on the vertical illuminance facing the window at a seated eye level of 1.22 m., but in this study, it was calculated along the whole depth of the office (front, middle, and back) instead of just the middle of the office as per the definition given by Osterhaus et al. [Osterhaus et al., 1992]. Sample values of *SR* along the depth of the office are tabulated for comparison with the corresponding ones for a clear-glazed window (Figure 4-12) in Table 5-10.

The positive/favourable effect of EC glazing on visual comfort compared to unshaded clear glazing is very distinct. With EC glazing of linear control, *SR* in the 'just intolerable' range is non-existent in the back and the middle of the office and occurs only 4.5% of the working year in the front, compared

SR	Percentage of Working Year								
	Clear Double Glazing			EC Non-linear Control			EC Linear Control		
	1 m.	3 m.	5 m.	1 m.	3 m.	5 m.	1 m.	3 m.	5 m.
Just intolerable	48.2%	12.3%	1.2%	5.7%	0.0%	0.0%	4.5%	0.0%	0.0%
Just disturbing	31.3%	51.0%	45.1%	74.3%	32.0%	1.3%	62.0%	7.3%	0.5%
Just noticeable	10.8%	26.6%	42.8%	10.5%	57.9%	87.8%	23.9%	82.6%	88.5%
Just imperceptible	0.0%	0.5%	1.4%	0.0%	0.5%	1.3%	0.0%	0.5%	1.3%

Table 5-10 Distribution of glare subjective rating as percentages of the working year due to a south-facing window with clear double glazing and with EC glazing (linear and non-linear controls)

to 1.2%, 12.3%, and 48.2%, respectively, with clear glazing. While during 62% of the time, *SR* in the front of the office still falls in the 'just disturbing' range, this occurs only 7.3% of the time in the middle and 0.5% in the back. Most of the *SR* values noted in the case of clear glazing to be in the 'just intolerable' and 'just disturbing' ranges have been 'relegated', with EC glazing and linear control, to the 'just noticeable' range. These 'just noticeable' *SR* values occur 23.9%, 82.6%, and 88.5% of the time, in the front, middle, and back of the office, respectively, as opposed to just 10.8%, 26.6%, and 42.8% of the time, respectively, in case of an unshaded window with clear glazing.

While the results for EC glazing with non-linear control are almost identical to those of linear control in the back of the office, linear control provides more preferable *SR* values in the front and middle of the office. With non-linear control, *SR* falls in the 'just noticeable' range only 10.5% of the time in the front of the office and 57.9% in the middle compared to 23.9% and 82.6%, respectively, with linear control. Conversely, non-linear control of EC glazing causes *SR* to be in the 'just disturbing' range more often than linear control, i.e., 74.3% and 32% of the time in the front and middle of the office, respectively, rather than 62% and only 7.3%, respectively, with linear control. This echoes the conclusions drawn from comparing the annual profiles of useful daylight illuminances for the two types of EC control in

Section 5.3.3.1 (non-linear) and Section 5.3.5.1 (linear), i.e., that linear control of EC glazing can provide a more visually favourable environment. As noted previously in Section 5.3.6, however, the downside of EC linear control is a higher consumption of energy for electric lighting compared to non-linear control.

5.4 Summary

In this chapter, the integration of switchable devices into the transparent area of a building envelope in order to control the admitted daylight was investigated. This was done by simulating the operation of responsive shading devices and the modulation of glazing transmittance in buildings of different azimuth orientations. The internal daylight illuminances were varied accordingly in order to predict the impact which these switchable devices can have on the illuminance distribution and the visual environment in non-domestic buildings. In addition, scenarios coupling the operation of these devices with the operation of different types of daylight-linked lighting controls were examined in order to predict the resulting consumption of energy for electric lighting. The aim was to investigate the possibility of improving the luminous environment in non-domestic buildings for a significant fraction of the working year while minimizing energy use, based on real time-varying sky and sun conditions. The daylight illuminance and energy results show that, in principle, EC glazing can offer such an opportunity. While automatic blinds coupled with continuous light dimming were shown to offer more favourable illuminance and energy performance to those associated with manual blinds and manual on/off light switching, plausible scenarios incorporating EC glazing produced considerably more favourable results.

In the next chapter, the focus will be on the opaque area of the building envelope and the notion of incorporating electricity-generating devices (namely photovoltaics) into it. Real time-varying meteorological data was utilized to assess the electricity generating capacity of building-integrated

PVs in order to realistically quantify their potential contribution to further reducing the net electric energy demand of buildings of different azimuth orientations.

Chapter

6

Advanced Envelope Systems II: Building-Integrated Photovoltaics

"Who doth ambition shun
And loves to live i' the sun,
Seeking the food he eats,
And pleased with what he gets."

WILLIAM SHAKESPEARE 1564-1616 (*AS YOU LIKE IT*, ACT II, SC. V)

In the previous chapter, it was described how switchable envelope devices and advanced lighting controls could potentially reduce primary energy consumption in office buildings by making effective use of available daylight. Another way of reducing the net primary energy consumption in buildings is to generate electricity in-situ using renewable energy sources. This is addressed in this chapter.

A sizable amount of our energy use takes place in buildings[1]. For example, buildings are said to account for almost 40% of the total energy

1. In addition, estimates suggest that urban populations will constitute 80% of the total world population by the year 2100 [Santamouris, 2001]

consumption in European Union countries and 36% of that in the U.S. [Selkowitz, 1999]. Additionally, buildings are reported to use 65% of all U.S. electricity [Santamouris, 2001]. This is accounted for by the need to heat and illuminate a building at different times of the day and year and by the ventilation and air-conditioning systems found especially in non-domestic buildings, i.e., shops and offices [ETSU, 1999a].

Decentralized power generation, i.e., from relatively small distributed sources (for example, photovoltaics), as opposed to generation from large, remote power stations, is receiving a considerable amount of attention at the global and national levels [Bazilian et al., 2000]. Using buildings to generate electricity is a plausible concept as high-value land then serves a dual purpose, and electricity is generated at the point of use (avoiding transmission and distribution losses). If the system is connected to the existing local grid, electricity is imported from the grid to cover any deficits, and excess electricity is exported when system production exceeds the load (for example on weekends when the building is unoccupied). This may also reduce the utility company's capital and maintenance costs (required to increase the production capacity) [Schoen, 1996]. Building-integrated photovoltaics, in particular, are regarded as an elegant method of installing electricity-generating renewable energy systems in urban built-up areas where undeveloped land is sparse and highly-priced [Toggweiler, 1999].

Photovoltaic cells are semi-conductor devices that generate electricity when exposed to sunlight. They are modular, silent, free from fuel and pollution during operation, and require minimum maintenance. They are being gradually considered for implementation within the urban environment [Munro, 1999]. The cost of integrating photovoltaic systems into the architectural design of buildings can be mostly or partly offset by replacing particularly expensive cladding material in prestigious commercial buildings. They also offer designers a novel component which can be used to create environmentally-friendly and energy-efficient buildings without forfeiting comfort or aesthetics [Toggweiler, 1999].

Worldwide, building-integrated photovoltaics (BIPV) are reported as the fastest growing sector of the overall PV market[2] [Steemers, 2001]. This is partly due to the intense national programmes that have been founded in countries such as the U.S., Japan, Germany, and the Netherlands. In contrast, the UK BIPV market is comparatively undeveloped, although more projects are being implemented [Buston, 1999].

A holistic approach to the design of BIPV systems has the potential to reduce a building's energy demand from the electric utility grid while generating electricity on site and forming part of the envelope/skin of the building. This integrated approach, incorporating energy conservation, energy efficiency, building envelope design, and PV technology, can in principle, maximize energy savings and take full advantage of opportunities to employ BIPV systems [Eiffert et al., 2000].

In this chapter, PVs in general and BIPVs in particular are reviewed. Design consideration issues relating to the integration of PVs into buildings are discussed in detail. Then, a model is devised to simulate the performance of a BIPV system integrated into the envelope of the office model, studied in the previous chapters, and calculate the PV electric output based on real hourly data of irradiation and ambient temperature for different facade orientations.

6.1 Photovoltaics

6.1.1 Introduction

The photovoltaic effect is the process in which a voltage is generated by the incidence of light on a material, i.e., the conversion of light energy into electrical energy [Roberts, 1996]. The fabricated devices which use this

2. The PV market is reported to be doubling every 3 years [Steemers, 2001]. In 2001, global production of PV cells and modules was up by 36% (i.e., compared to that in 2000), and in Europe, that figure was 42% [Maycock, 2002]. Grid-connected systems are considered particularly prominent [Steemers, 2001]. Worldwide, the grid-connected PV sector (residential/ commercial) grew by 67% [Maycock, 2002].

process to convert light into electricity are called photovoltaic (PV) cells. They are large area semi-conductor diodes, usually silicon wafers 100 cm^2 in size, and which normally generate a voltage of approximately 0.5 V and a current of approximately 3 A (1.5 W) in full sunlight [Boyle, 1996][CIBSE, 2000]. For most applications, PV cells are mounted/assembled in 'modules', typically 36 or 72 cells connected in series, to produce a higher, more useful voltage [IEA-PVPS, 2000].

PV cells use both components of the solar radiation (direct and diffuse), and so they can still produce electricity when the sky is overcast, albeit less than under a bright sunny sky. However, PV cells use mainly the visible range of the solar radiation. Since the majority of the sun's energy is in the infra-red (IR) and ultra-violet (UV) regions, this explains why the theoretical maximum PV conversion efficiencies are only 20 - 30% [IEA-PVPS, 2001a]. Practical deficiencies in the material, such as impurities, may decrease the performance of a PV cell even further.

6.1.2 PV Cell Materials

The photovoltaic effect can be generated with various materials, and thus, many products are being developed with the aim of reducing costs and increasing efficiencies. There are, however, four semi-conductor materials which are currently in production or pre-production for PV cells, and which exhibit reasonable energy conversion efficiencies. Cells made of crystalline silicon and of amorphous silicon are commercially available, those made of cadmium telluride (CdTe) and of copper indium diselenide (CIS) are in pilot production (not yet in wide-spread commercial production), and modules using copper indium gallium diselenide (CIGS) are still in the testing stages [Hill, 1998].

Crystalline Silicon

The efficiency[3] of the best research silicon cell reported so far is 24%[4] [Hill, 1998]. Commercial cells have efficiencies of around 13 - 17% for monocrystalline and 12 - 15% for polycrystalline (the corresponding modules have efficiencies of 12 - 15% and 11 - 14%, respectively) [CIBSE, 2000]. While monocrystalline silicon cells are the most efficient, they are also the most expensive. Polycrystalline silicon cells are cheaper and can be larger. One of the promising research areas is thin crystalline cells, where the aim is to reduce the amount of material used in the cell whilst maintaining high efficiency by incorporating light trapping techniques [Hill, 1998].

Amorphous Silicon

Amorphous silicon (a-Si) is cheaper to produce than crystalline silicon but has a significantly lower efficiency. The output of modules with single junction amorphous silicon degrades rapidly in outdoor applications over the first few months, by perhaps 30%, falling from an initial efficiency of 4 - 7.5% until a stabilized efficiency is attained [Hill, 1998][CIBSE, 2000]. However, the overall conversion efficiency of amorphous silicon can be improved by layering two or more PV junctions on top of one another. The best efficiency reported so far for a triple-junction amorphous silicon cell is 13.6% [Hill, 1998].

Cadmium Telluride (CdTe)

Research CdTe cells with efficiencies above 15% have been produced, but at present, modules of CdTe cells usually have efficiencies of around 8% and are reported to show no degradation either in the field or under accelerated testing [Hill, 1998].

3. The efficiency is the ratio of the output power to the incident solar radiation.
4. It should be mentioned that in November 2001, it was announced that a triple-junction terrestrial concentrator solar cell, designed and built by *Spectrolab, Inc.*, had achieved a world-record conversion efficiency of 34% in laboratory tests [REW, 2001].

Copper Indium Gallium Diselenide (CIGS)

The highest efficiency reported to be achieved by a research CIGS cell is 17.5%. Modules with an efficiency of 11% have been demonstrated, but the average efficiency of the commercial module is expected to be around 8% [Hill, 1998].

Novel Materials

Other developments in the research of novel PV materials include the dye-sensitised nanocrystalline semiconductor devices, developed in the Ecole Polytechnique Federale de Lausanne (EPFL) in Switzerland, and 'thermophotovoltaics' (TPV), which are of lower bandgaps than conventional PV cells and designed to convert thermal energy (rather than light energy) to electricity, i.e., they can respond to longer wavelengths emitted by a high temperature heat source [Pearsal, 1999].

6.1.3 PV Modules

In 1997, approximately 87%[5] of commercial PV modules were reported to have used silicon[6] wafer cells (mono- and polycrystalline), and in 2001, that figure was over 80% [Hill, 1998][Maycock, 2002]. As noted earlier, in a module, the PV cells are connected in series to give the required output voltage. The 'cell string' is hermetically sealed (encapsulated) using soft rubber or ethylene vinyl acetate (EVA) and laminated between a sheet of low-iron tempered glass at the front and a back cover of either glass or an opaque material (Tedlar, which is a kind of plastic available as either opaque or transparent, is frequently used) for protection. This laminate (i.e., frameless module), or one which is bounded by an aluminium frame (to give it mechanical strength and a means of attaching the module to a frame), forms the commercial module. Figure 6-1 shows a typical construction of a

5. This percentage consisted of 50% monocrystalline, 34% polycrystalline, and 3% ribbon (in which silicon is grown as 10-cm. wide ribbons and cut into 10-cm. lengths) [Hill, 1998].

6. Note that silicon is a highly abundant material since it constitutes more than 25% of the earth's crust [Eiffert et al., 2000].

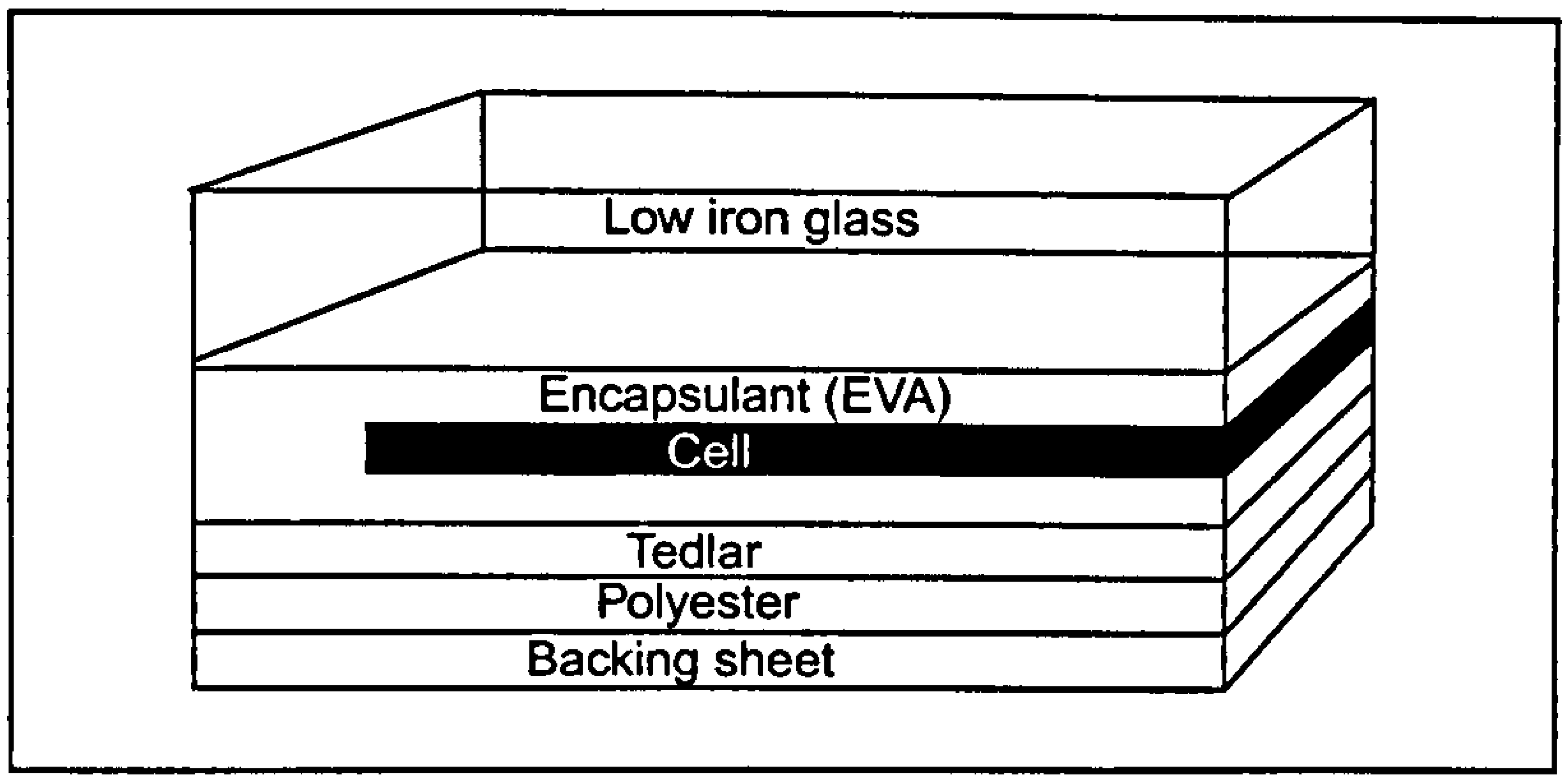

Figure 6-1 Typical crystalline silicon module construction [re-drawn from CIBSE, 2000]

crystalline silicon module. Generally, the thickness of a glass-Tedlar laminate is 8 mm., while glass/glass laminates are at least 10 mm. thick [IEA-PVPS, 2001a].

The power produced by a PV module is the product of the operating voltage and current. To increase the power output of a PV system, modules are usually connected together to form an array. The number of modules connected in series (series string) determines the system voltage, and the number of series strings connected in parallel determines the system current [CIBSE, 2000]. For connecting the PV modules, either in series or parallel, most modules are fitted with a junction box (5 - 7 cm. deep) at the rear side [Roberts, 1996].

Modules are less efficient than cells for two main reasons. Firstly, the area of a module is always greater than the combined area of the cells by 10 - 20% so the collecting efficiency (i.e., with respect to the total area) is correspondingly lower [Hill, 1998]. Secondly, PV cells in a series string must carry the same current, so any difference in the performance of the cells results in the output being dependent on the characteristics of the poorest/ worst cell in the string (termed mismatch losses). It is, therefore, standard for each cell to be tested after manufacture and the cells to be arranged into groups with closely similar current/voltage characteristics. Modules are then assembled of strings of cells from the same group so as to reduce these mismatch losses [Hill, 1998].

A PV system consists of one or more modules together with the electronic controls, storage units, DC-to-AC inverters, mounting structures, and wiring. All elements other than the PV modules are together known as the balance of system (BOS) components. The cost-effectiveness and reliability with which a PV system performs depends as much on the BOS components as on the PV modules themselves, and their future developments are considered important factors in the future prospects of PVs. In fact, it has been reported that where PV systems have failed in the past for technical reasons, it has generally been due to inadequate system design and/or poor choice of BOS components, rather than failure of a PV module [Hill, 1998]. Therefore, significant international research efforts are currently aimed at improving the performance of BOS components [IEA-PVPS, 2001a].

The PV industry currently has over 20 years of field experience with modules of the construction described above, and they have proved to be extremely reliable[7]. Modules are usually rated between 50 and 200 W_p[8], although several PV manufacturers currently offer modules above 200 W_p [IEA-PVPS, 2000]. The major PV manufacturers offer power production warranties for PV systems for as long as 10, 20, and 25 years. These manufacturers promise to replace the power output lost from modules that fail to produce at least 80% of the minimum power output specified on the module's data sheet [Eiffert et al., 2000].

6.1.4 Electrical Characteristics of Silicon PV Cells and Modules

There is an international agreement that the performance of PV cells and modules should be measured under a set of standard test conditions (STC).

7. Modules are proclaimed to show failure rates below 0.1% per year [Laukamp et al., 2000]
8. W_p is peak power output in watts of a PV module under standard test conditions [CIBSE, 2000].

These essentially specify that the temperature of the cell or module should be 25°C, and that the solar radiation incident on the cell should have a total power density of 1000 W/m^2, with a spectral power distribution[9] known as Air Mass 1.5. The nominal power that the module produces under STC is quoted as the 'nominal peak power' for that module (measured in watts peak, W_p).

The electrical characteristics of a PV cell or module tested under standard test conditions are often summarized by an $I - V$ curve where I represents the generated current and V represents the generated voltage. When no load is connected, i.e., when the resistance is infinite, the current in the circuit is at its minimum (zero) and the voltage across the cell is at its maximum, known as the 'open circuit voltage', V_{oc}. At the other extreme, when the resistance is zero, the cell is effectively 'short circuited', and the current in the circuit reaches its maximum, known as the 'short circuit current', I_{sc}. By varying the resistance between zero and infinity, the current, I, and the voltage, V, will be found to vary as shown in Figure 6-2, (i.e., an $I - V$ curve). It can be seen from the graph that the cell will produce maximum power (i.e., the maximum product of voltage and current) when the external resistance is adjusted so that its value corresponds to the maximum power point, MPP, on the $I - V$ curve. At solar radiation levels lower than the maximum of 1000 W/m^2, the general shape of the I-V characteristic remains the same, but the area under the curve decreases, and the maximum power point shifts to the left [Boyle, 1996].

The short circuit current is directly proportional to the intensity of solar radiation incident on the PV cell while the open circuit voltage is only slightly dependent on the solar radiation intensity (it increases logarithmically) [Boyle, 1996][Duffie et al., 1991]. On the other hand, the

9. The spectral power distribution is a description of the way in which the power contained in the solar radiation varies across the spectrum of wavelengths. The concept of 'Air Mass' is related to the way in which the spectral power distribution of radiation from the sun is affected by the distance the sun's rays have to travel through the atmosphere before reaching a PV module [Boyle, 1996].

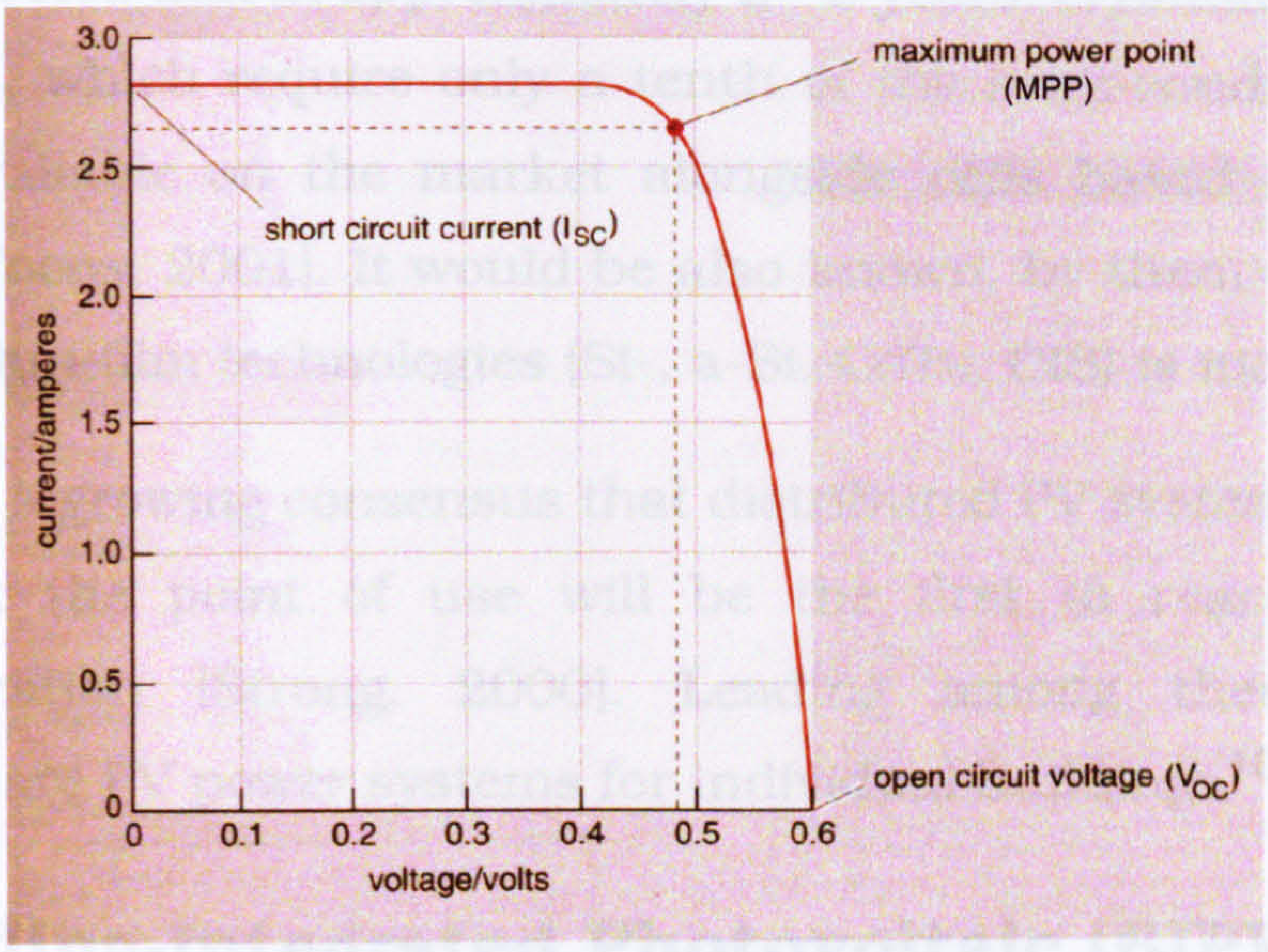

Figure 6-2 Current-voltage (*I-V*) characteristics of a typical silicon PV cell under standard test conditions [Boyle, 1996]

open circuit voltage decreases linearly as the cell temperature increases. For every degree rise in temperature of crystalline silicon cells above the STC temperature (25°C), the drop in voltage is approximately 0.4% (or approximately 0.0022V/(cell.degree)), while the short circuit current slightly increases by approximately 0.07% [IEA, 1996].

When PV cells are producing power to electrical loads under real-world conditions, the intensity of solar radiation often varies considerably over time. Many PV systems, therefore, incorporate a 'maximum power point tracking' (MPPT) device, which is a specially designed electronic circuit that automatically varies the load as 'seen' by the PV cell in such a way that it is always operating around the maximum power point and so presenting maximum power to the load [Boyle, 1996].

6.1.5 Future of PVs

Reports suggest that in the near future, crystalline silicon PV cells will still be the most prevalent [Maycock, 2002]. It is expected that use of less material and mass production are likely to keep them competitively-priced for many years ahead, with a probable efficiency of 20% [RE-Focus, 2001]. It is also expected that in approximately 2 - 5 years, crystalline silicon thin-film PV cells, which require only a tenth of the semi-conductor material, would be available on the market alongside cells based on amorphous silicon [RE-Focus, 2001]. It would be also known, by then, which markets each of the thin-film technologies (Si-, a-Si, CdTe, CIS) is most suitable for.

There is also a growing consensus that distributed PV systems that provide electricity at the point of use will be the first to reach wide-spread commercialization [Strong, 2000]. Leading among these distributed applications are PV power systems for individual buildings[10].

6.2 Building-Integrated Photovoltaic (BIPV) Systems

For almost three decades, PV systems have been successfully used in off-grid applications, such as, telecommunications, light-houses, navigation buoys, street lighting, emergency telephones, road signals, water pumping, refrigeration, and electrification of remote homes. These stand-alone installations usually contain some storage devices (such as batteries) if operation is required at night.

In the late 1980s and early 1990s, integrating PV systems into buildings started being considered seriously in a few countries, and a number of demonstration programmes were set up [Munro et al., 1996]. Now, projects have been successfully realized all around the world[11]. The technology for integrating PV modules into buildings has established a robust foundation, and significant research and development efforts have been carried out

10. In 1992 when IEA-PVPS (International Energy Agency - Photovoltaic Power Systems Programme) began, 29% of the cumulative installed PV generation capacity was grid-connected. In 2001, this figure was 61% (437MW), largely due to the Japanese and German programmes in recent years (109 MW and 44 MW, respectively). Over 90% of the grid-connected capacity is now in distributed generation systems [PVPower, 2001].

11. The International Energy Agency (IEA), through its Task VII - Photovoltaic Power Systems in the Built Environment, has evaluated and categorized existing projects and set up a comprehensive database of a large number (over 300) of BIPV projects world-wide [IEA-PVPS, 2001b]. The database was developed to provide references for architects, engineers, and researchers.

through programs on national and international levels [Schoen, 1996]. The technology has advanced from the research laboratory to commercial applications, and it is considered ready for expanding commercialization. Innovative architects are beginning to integrate PVs into their designs, and PV manufacturers are reciprocating with modules specifically produced for BIPV applications, including integral roof modules, roofing tiles and shingles, and modules for vertical curtain wall facades, sloped glazing systems, and skylights [Strong, 2000]. Owners of commercial buildings are also beginning to show interest in installing PV systems as a highly prestigious feature of their property[12]. Projects are currently being realized with limited or no government support[13] [Schoen et al., 2000b].

6.2.1 Advantages of BIPV Systems

While large central-station utility-scale PV plants covering vast areas of land have many advantageous aspects (such as flexibility in system layout), the downsides include the costs of the site development (and land), support structures, electrical distribution, utility interface, real estate taxes, and transmission and distribution losses. Centralization also ignores the advantages offered by the modular, distributable nature of PV technology. Further, in places such as Europe and Japan, the scarcity of large open areas of land effectively excluded the central-station PV option [Strong, 2000]. Rather, aggressive efforts, begun in the early 1990s, particularly in Europe and Japan, have promoted the technology of integrating PVs into the urban environment for wider commercial acceptance [Munro, 1999].

12. A notable example is the '4 Times Square' building in New York [Durst, 2002][Kiss et al., 2002].

13. For example, the solar grants currently available in the UK from the EST towards the installation of PV equipment (40% - 65% of the total installation costs) for domestic and non-domestic buildings [EST, 2002].

Building-integrated PV systems have a number of advantages, summarized in the following points:

- No additional land or separate support structure are required for the PV system as the modules become an integral part of the building envelope. The land is already paid for, and the supporting structure is the building itself.
- PV modules integrated into the building structure replace other parts of the building walls, roof, or glazing, thus offsetting part of the construction and labour costs and increasing the cost effectiveness of the PV system.
- Power is generated at the point of use so transmission and distribution losses are avoided.
- Operating in a grid-connected mode avoids the need for storage devices.
- BIPV systems present a huge potential to innovative architects and building designers, supplying them with a valuable tool for advancing the aesthetics, architectural quality, and 'green' self-sufficient appearance of buildings.

PV systems are regarded as particularly suitable for integration into commercial and office buildings where the PV output is most likely to match the energy load profile of the building, i.e., during daylight hours when PV cells operate and the buildings are occupied. Moreover, the costs of cladding a commercial or office building with PV arrays are already comparable with those of the higher cost building materials (for example, marble and polished stone) which may be used in the construction of 'premium' buildings (see Table 6-1) [ETSU, 1999a][CIBSE, 2000]. In the case of BIPV systems, however, they have a dual function: acting as cladding/roofing and as power generators.

6.2.2 Design Considerations

The output from a building-integrated PV system is the output of the PV array minus the losses of the rest of the system [ETSU, 1999b]. The output from the PV array depends on the following factors:

- Solar radiation at the site.
- Azimuth orientation.
- Tilt angle from the horizontal.
- Temperature.
- Shadowing.

These factors are discussed in more detail below.

6.2.2.1 Solar Radiation, Azimuth Orientation, and Tilt Angle

While the maximum output of a PV system is valuable for calculating peak supply, the annual energy production is regarded as more important when considering grid-connected systems [ETSU, 1999b]. This depends on the annual availability of the solar radiation at the site. The maximum annual incident solar radiation, and hence, the PV output in unshaded installations, is usually at the orientation of due south (in the northern hemisphere), or approximately of due south, and a tilt from the horizontal equal to the latitude of the site minus approximately 20° [ETSU, 1999b][CIBSE, 2000], Figure 6-3. For any combination of tilt angle and orientation, the power output from an unshaded PV array can be estimated using meteorological data and computer programs that incorporate various modelling assumptions, for example, uniform sky, no shading/inter-reflections, etc..

6.2.2.2 Temperature

As discussed earlier, while the instantaneous power output from the PV cell is directly proportional to the intensity of solar radiation incident on it, it is inversely proportional to the temperature of the cell [Scott, 1996]. It has

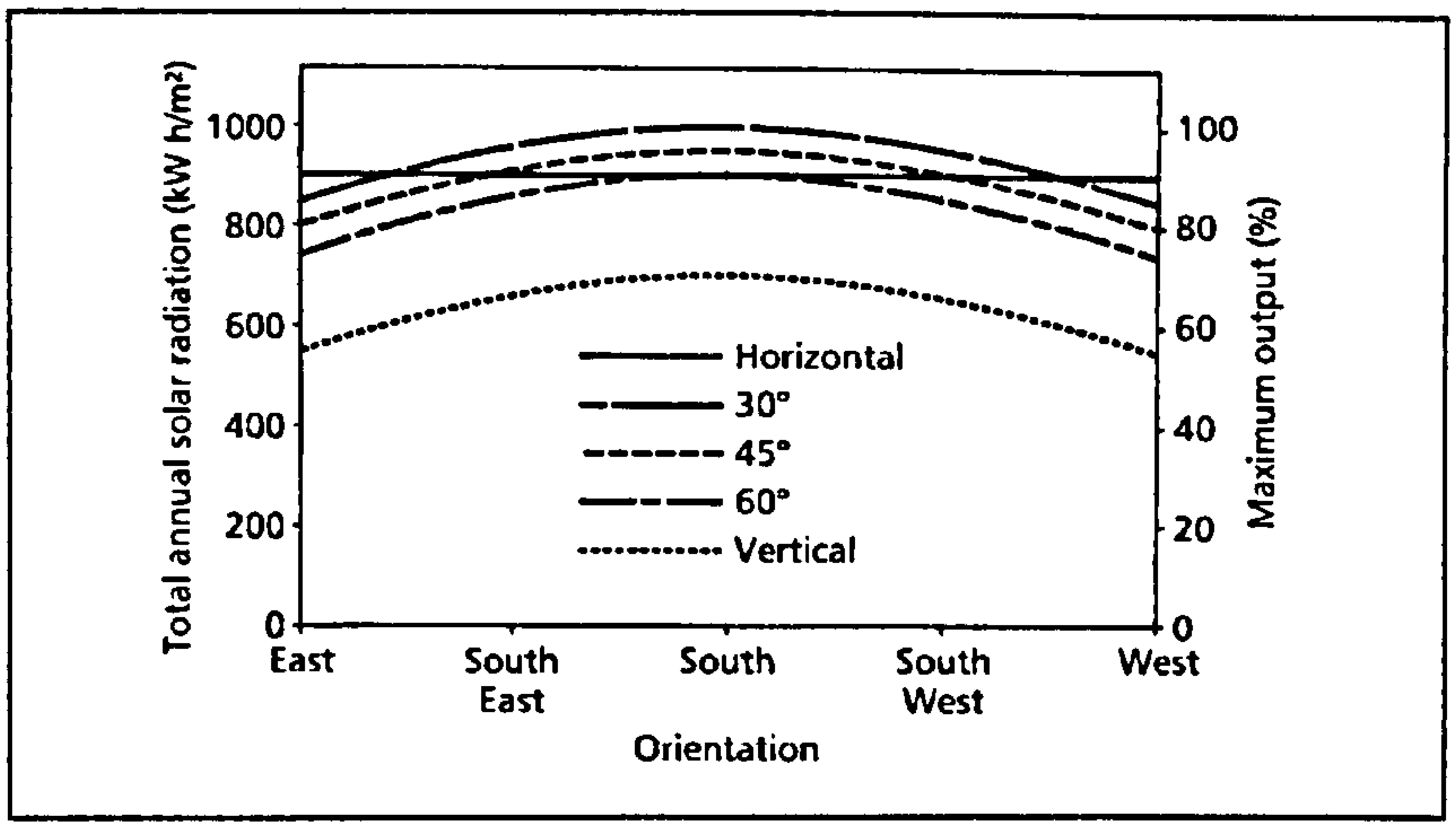

Figure 6-3 Effect of tilt and orientation on power generation based on data for Kew (51.47N, 0.28W), UK [CIBSE, 2000]

been reported that building-integrated modules can reach 20 - 40°C above ambient in conditions of high solar radiation [CIBSE, 2000]. For each 1°C rise in cell temperature above 25°C, the power output decreases by approximately 0.4 - 0.5% for crystalline silicon and by approximately 0.25% for amorphous silicon (i.e., assuming 100% of power output at 25°C), depending on module design [ETSU, 1999b][Bazilian et al., 2000]. At temperatures above 90°C, the EVA encapsulant breaks down [CIBSE, 2000]. Designs for BIPV installations, therefore, need to permit sufficient ventilation, whereby circulating air cools the backs of the PV modules in order to maintain their high performance. This excess heat can be vented off or, alternatively, used for space or water pre-heating[14] or for drawing air through the building, hence assisting natural ventilation [Crick et al., 1996].

In general, it is recommended that a minimum air gap of 10 cm. needs to be provided behind the building-integrated modules to allow for cooling by natural buoyancy effects [ETSU, 1999b]. Some studies, however, suggest that performance can be improved with gaps of 15 - 25 cm [Fuentes,

14. Hybrid PV systems (i.e., electrical and thermal) can reach overall efficiencies of 40 - 50% [CIBSE, 2000].

1987][Brinkworth et al.,1997]. The flow of air in the gap can also help ensure that a PV facade does not contribute additional heat gains within the building thus increasing its cooling load [Crick et al., 1996].

It should be noted, however, that the optimum width of the air gap would depend on the geometrical and optical characteristics of the module and the mounting/building structure. Moreover, based on the thermal mass of the PVs and the other facade elements, there is expected to be a phase shift of a few minutes between the maximum irradiance incident on the facade and maximum temperatures of the PV cells and the air in the gap [Eicker et al., 1998].

6.2.2.3 Shadowing

In urban areas, overshadowing by other structures is customary, for example, from trees, chimneys, and other buildings, in addition to self-shading due to the architectural shape of the building. This should be taken into consideration starting from the initial design stages of BIPV installations and minimized, wherever possible, as even minor shading can result in a considerable loss of energy. Because of the connection in series of the PV cells and modules, shading of any part of the array will influence the output of the whole system, Figure 6-4. This is because the cell with the

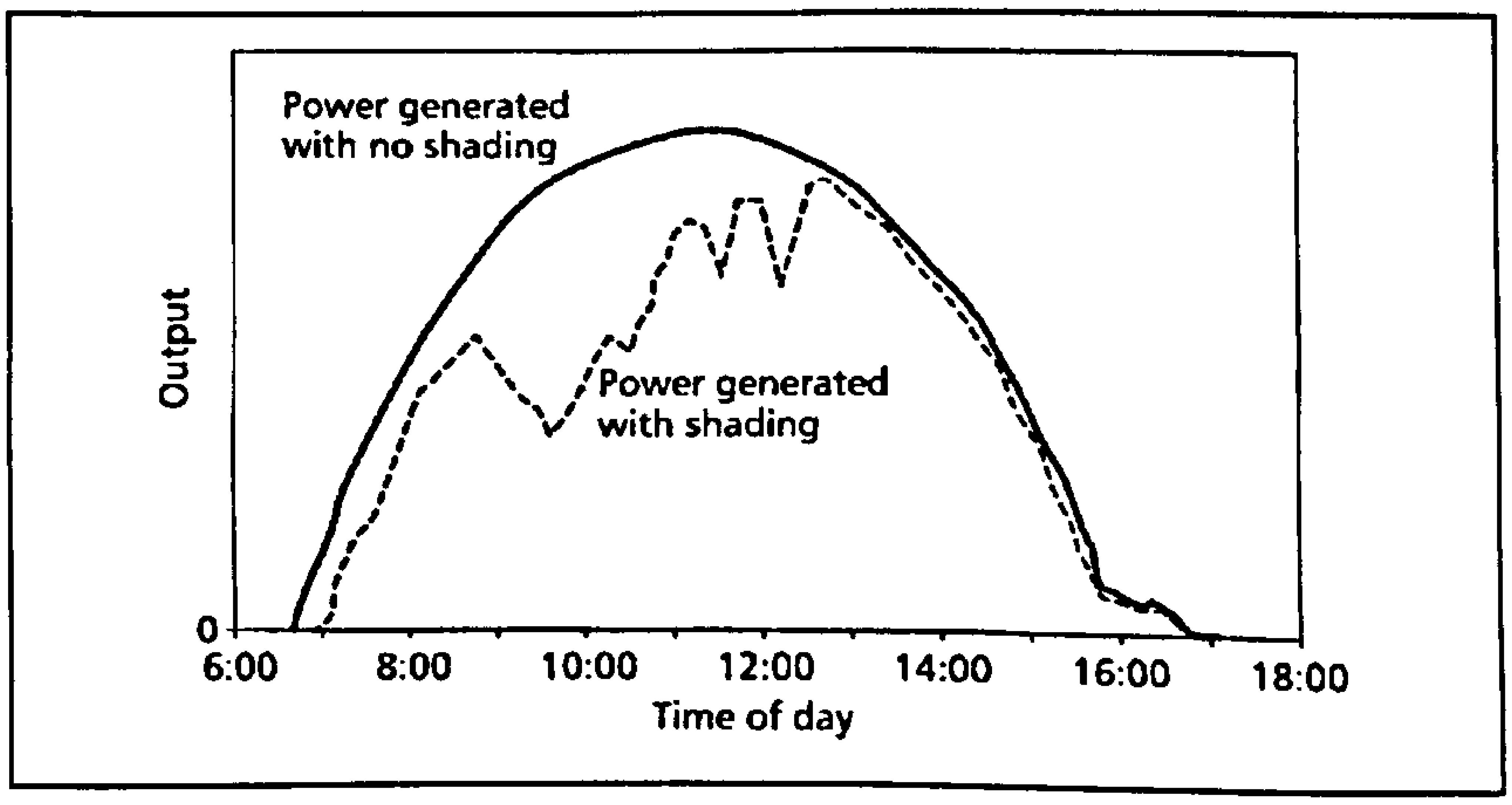

Figure 6-4 An example of the effect of shading on power output from a PV array. The shading was caused by a handrail at the edge of a roof-mounted monocrystalline array [CIBSE, 2000]

lowest incident illumination determines the operating current of the series string in which it is connected. Ideally, there should be minimum shading during the middle six hours of the day, i.e., when the sun is within 45° of due south (in the northern hemisphere) [CIBSE, 2000].

However, prudent selection of the components and design configuration of the array can help minimise the losses due to shading on the whole array. For example, string inverters, where strings of modules are handled by separate inverters, can react to shading better than a central inverter when the group of cells/modules with anticipated shading are connected together in the same string [CIBSE, 2000]. Additionally, installing protection elements such as bypass diodes could help protect the solar cells from permanent damage since localized shading of one of the cells in a module would make it act as a load causing it to overheat (hot-spots).

6.2.3 New Approaches: Semi-Transparent BIPV Systems

As discussed previously, the benefits of daylighting in the built environment have been re-discovered in the last decade. Since PV panels are considered adaptable for daylight transmission, semi-transparent BIPV systems have gained particular interest in recent years. Semi-transparency can be achieved using either crystalline or amorphous silicon module types. Monocrystalline or polycrystalline cells can be spaced apart in the laminate module design in order to incorporate clear-glazed gaps of almost any required size. Laser-etched grooves can also be applied to crystalline and amorphous modules in a wide variety of patterns. Many buildings which incorporate this semi-transparent BIPV technology have been constructed in several countries in Europe, USA, and Japan in the last few years [Bazilian et al., 2000].

An important design issue for semi-transparent PV integration is the ratio between the transparent and opaque (PV cells) sections of the PV facade or roof. The larger the transparent gaps, the more the daylight and solar heat gain, but less electricity is produced. Moreover, the area, position, and shape of those transparent gaps influence the internal daylight distribution. [Vartiainen et al., 2000] While small transparent sections mean large PV sections and more electric output, they would provide little natural illumination to the interior. The occupants, in this case, would resort to using artificial lighting, thus increasing the energy load of the building and eliminating the benefit of any additional electricity produced by the PV system. Therefore, in addition to adoption of energy efficiency strategies, an overall energy consideration of the building as a whole is required for the successful implementation of such innovative technologies.

6.2.4 PV Building Elements and Their Integration

An expanding range of PV building materials is currently available or under development, such as, roof tiles, roof cladding, facade elements, windows, shading devices, etc.. Because these PV building elements perform dual functions, they are being developed in such a way that established/ standard design objectives would not be compromised. This means that PV building elements are designed to function in the same way as that required/expected from conventional building materials, for example, with regards to protection from the elements and noise, and providing light, warmth, security, and privacy.

A further advancement in the aesthetics of BIPV modules is the development of coloured PV silicon cells. This, however, comes at the cost of some reduction in PV output power. Using different thicknesses of the anti-reflective coating, the colours currently available on the market from a number of manufacturers include green, magenta, gold, pink, and steel blue. This is in addition to the original colours of dark blue or dark grey for crystalline cells and black or dark brown for amorphous silicon [ETSU, 1999a]. The drop in efficiency (for example, approximately 20% for magenta or gold compared to blue) is attributed to the fact that their colour comes from reflection of some of the light which would otherwise be absorbed [CIBSE, 2000].

There are essentially three basic ways of integrating PVs into buildings:

- Roof-based systems.
- Facade systems.
- Rainscreens and sunshades.

6.2.4.1 Roof-based Systems

Roofs are considered quite appealing locations for installing PVs. They are often devoid of shading (except in dense urban environments), are likely to be easier to ventilate than facade systems, and a sloped array can be constructed to promote high performance from the PVs. PV roof tiles (readily integrated with conventional tiles) or PV panels can be used for inclined roofs, while the panels can be used for flat, curved, or saw-tooth north light roofs. For atria and skylights, semi-transparent PV panels can be used to allow daylight to seep through.

6.2.4.2 Facade-based Systems

Facades, whether vertical or inclined, have significant potential for PV integration. They are highly visible so can be used (by the developers/ designers) to make a clear statement (green/sustainable), promoting environmental awareness and/or architectural innovation. Facades usually have much larger areas than roofs[15], and much PV cladding can be considered to be panes of glass to which PV cells are applied, and so the long experience in the installation of glazed facades can be beneficial [ETSU, 1999b]. PV panels can be used in curtain walling systems, which are a well-established technology used in several prestigious buildings. The double-glazed units can be replaced by a combination of laminated opaque or semi-transparent PV panels and clear glazed sections.

15. In urban areas, where there is an abundance of high-rise buildings, vertical walls are plentiful for mounting building-integrated PV panels as cladding or shading devices [Jie et al., 2002].

6.2.4.3 Rainscreens and Sunshades

Rainscreen cladding systems are also suitable for applications of PV panels where the rear gap allows for ventilation of the PVs and provides space for cable routes [ETSU, 1999b]. These systems have potential in retrofit as well as new-build. PV panels can also be used in fixed or moveable awnings and sunshades in order to enhance building aesthetics. In addition to providing shading, the tilt of the sunshades can allow for the optimization of PV output (Section 6.2.2.1) and allow for ventilation of the back of the PVs.

Costs for BIPV systems have been decreasing and are expected to decrease further as the market grows and technology improves [CIBSE, 2000]. Table 6-1 presents some comparisons between the costs of BIPV systems and those of the conventional cladding material they can replace.

PV System / *Building Element*	**Installed Cost (£/m^2)**
PV curtain walling, glass/glass crystalline modules	780
PV curtain walling, glass/glass thin film amorphous modules	250
Conventional wall systems:	
• *double glazing*	*350*
• *cavity wall (brick/block)*	*50 - 60*
• *stone cladding*	*300*
• *granite faced pre-cast concrete*	*640*
• *polished stone*	*850 - 1500*
PV (crystalline) rainscreen cladding	600
Steel rainscreen overcladding	*190*
PV (crystalline) roofing tiles (housing estate)	500
Roofing tiles (clay or concrete)	*32*
PV (crystalline) modules on a pitched roof (large office)	650
Aluminium pitched roof	*44*

Table 6-1 Comparison of costs (in GBP) between BIPV systems (including BOS) and conventional building elements (at 1999 prices) [CIBSE, 2000]

6.2.5 Sizing BIPV Systems

The term 'sizing' refers to estimating the production capacity required from the PV system and hence, the power and number of modules/panels to constitute the array, i.e., the 'size' of the array. Sizing of PV systems can be performed using computer simulations which can match the predicted load profile of the building (over the year/day) with the energy output from the PV system, estimated using solar irradiation data available for the location. However, the sizing of the array is likely to be also influenced by other non-technical factors, such as the budget available for the PV installation, the available area of facade or roof, and the price which will be paid for the electricity sold to the grid and any costs involved with exporting electricity (if PV electricity is expected to exceed demand). Currently, unlike in other European countries (such as Germany and the Netherlands), the selling price in the UK for electricity exported to the grid is likely to be still lower than the price of imported units [CIBSE, 2000]. Hence, at present, it is wise/practical for the PV system to be sized such that its output does not exceed the base demand of the building (i.e., all the PV-produced electricity will be used in the building). If the power produced by the PVs cannot all be used on site, in some instances, it may be economic to supply the surplus PV power directly to a third party (for example, to another building in a business park), rather than export it to the grid.

6.2.6 Electrical Integration of BIPV Systems

The main components of a grid-connected PV system are outlined in Figure 6-5. The direct current (DC) electricity generated by the PV array is converted to alternating current (AC) before it can be used in parallel with the mains electricity or exported to the grid, but there is a small drop in system efficiency as a result of this conversion. The inverter is required to convert the DC to AC which is compatible with the voltage, phase, power factor, and frequency characteristics of the grid [CIBSE, 2000]. The selection of an inverter is normally based on its rated power (usually 75 - 80% of the array rating[16]), efficiency (generally over 90% when operating above 10% of its rated output[17]), and self-consumption losses (0.5 - 4% of the rated DC power is used to operate the inverter) [CIBSE, 2000][IEA-PVPS, 2000].

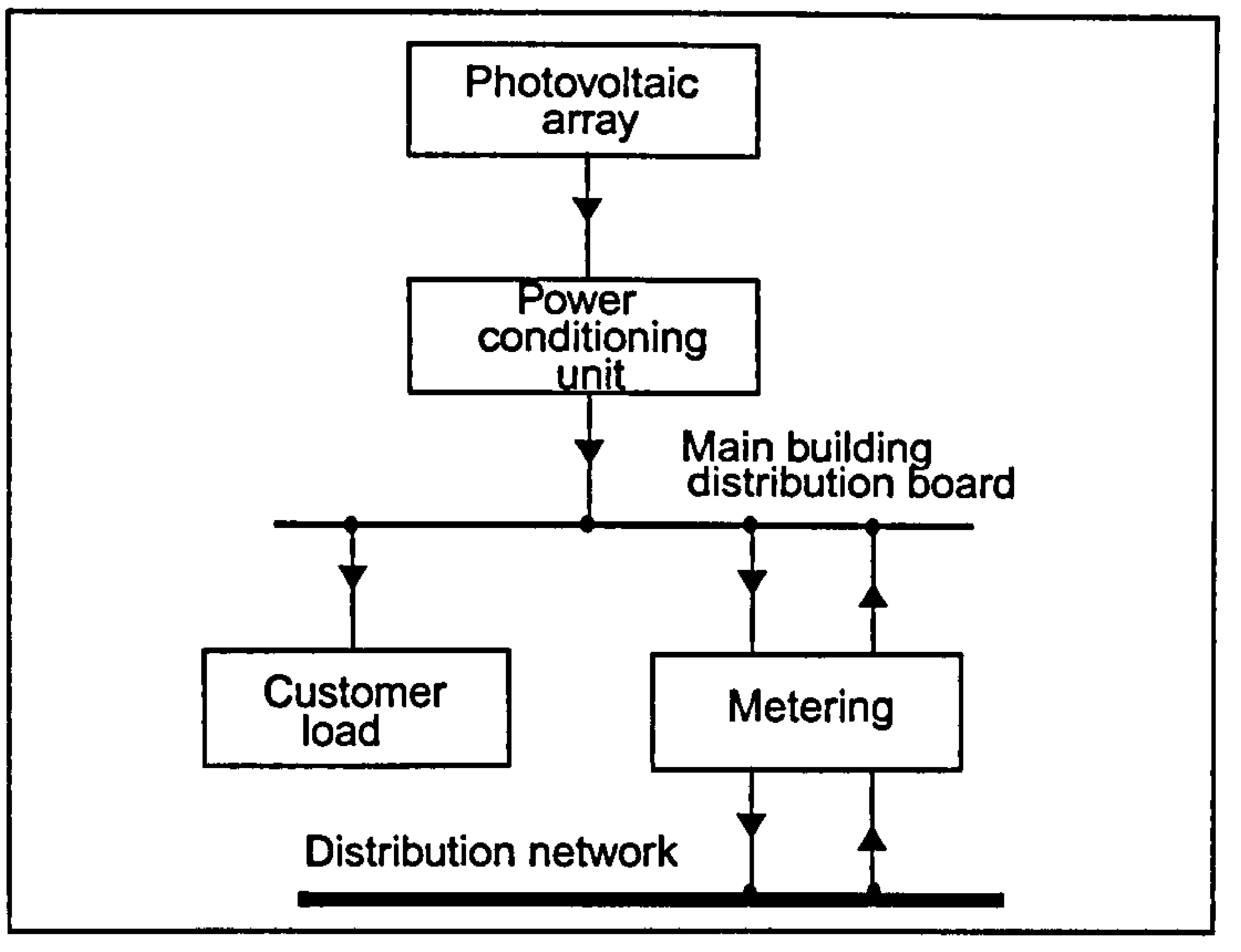

Figure 6-5 Block diagram of a grid-connected PV system [re-drawn from CIBSE, 2000]

Since, as mentioned previously, the output from the PV array will be highest if it is operated close to the maximum power point (MPP) under all conditions, the inverter often includes a maximum power point tracker (MPPT) which alters the input voltage in order to maintain this. Reliable/ proper tracking can be crucial for the performance of crystalline silicon arrays but is considered less critical for thin film amorphous arrays [CIBSE, 2000].

The PV DC output is typically tied to the AC building grid with a single central inverter or multiple (smaller) distributed inverters (called string inverters). The latter option is considered preferable to allow more security of supply (through independent operation) and simpler system expansion. Employing string inverters also allows for the use of different types of PV modules in one system, accurate monitoring, and MPP-tracking of every

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16. In building-integrated systems, often with a less than optimum orientation, the nominal power of the PV array is seldom harnessed. Thus, depending on the location and the PV array orientation, the inverter may be under-sized for an economically optimum design [Peippo et al., 1998].

17. Inverters, generally, have efficiencies of 90 - 96% for a full-load and 85 - 90% for a 10% load [EUREC, 1996].

individual string, and reduces DC cabling losses, thus resulting in improved performance [ETSU, 1999b].

In many commercial buildings, the PV DC output can be utilized for large DC loads and/or load management equipment readily available in the building. These equipment include uninterruptible power supply (UPS) units, variable speed drives for ventilation and cooling systems, fluorescent lighting, computers, and power conditioners (PCONs) [Lund et al., 2000]. In this case, during working hours (when the building is occupied), almost all the electricity generated by the PV system can be utilized within the building, thus simplifying the grid inter-connection (only import and no export) and avoiding the problems related to low buy-back rates of the utility [Lund et al., 2000].

Innovative storage devices such as fuel cells are also an option for BIPV installations. Although these devices have yet to prove their commercial viability, when sized appropriately, they can help ensure the reliability of the electric supply to the building[18], as well as help match peak electricity demands, thus offsetting some of the need for imports from the grid [DiFilippo, 1998].

It should be noted that when sizing a PV system, allowance has to be made for losses in the balance of the system (BOS), which typically total to approximately 15%. These are primarily losses due to the inverter (10 - 15%) and wiring losses (1 - 3%). In addition to the BOS losses, there are losses due to temperature effects, dust accumulation, mismatch, etc., which collectively decrease the energy output by approximately 10% [CIBSE, 2000].

18. For example, many commercial buildings have a sizable number of computers, and interruption of supply to them is considered very costly. In those cases, the risk of such interruptions and the associated losses can justify utilizing storage devices such as fuel cells or a UPS [Lund et al., 2000]

AC-Modules

An AC-module is a single PV module, with a typical power output of approximately 100 - 200 W_p, equipped with a small/micro DC-to-AC inverter, which is fitted onto the back of the module. The result is a fully integrated product, ready to install and easy to connect to the local grid. High outputs and efficiencies have been reported through building projects incorporating AC-modules in Europe [Schoen, 2001]. The primary reason for the high performance has been attributed to the lack of mismatch and DC losses between different modules (since the use of DC cabling is eliminated). Hence, each module operates at its maximum power point. In addition, installation and design is considered simpler since DC wiring expertise is not needed, nor is costly DC safety equipment [Stamenic et al., 1999].

Moreover, since an inverter requires a minimum amount of power from the PV array before switching on, with the low 'start/stop thresholds' (and low 'stand-by power' demand) of the micro-inverters integrated with AC-modules, system performance is expected to be improved since very little of the incident irradiation (and consequently, the PV generated electricity) is wasted[19] [Stamenic et al., 1999]. PV arrays which are able to operate at low insolation levels are considered particularly useful in locations where a significant part of the annual irradiation occurs during low-light conditions or cloudy weather, as for example in the UK. It is also particularly beneficial in urban areas where losses due to the BIPV array's non-optimum tilt and orientation and/or shading are sometimes unavoidable.

However, this type of module has so far been regarded as only suitable for small PV systems due to the fact that, currently, the inverter is still the primary cause of system faults [Schoen, 2001][Brouwer, 2000]. In larger BIPV systems, the AC-module inverters will be distributed throughout the

19. While monitoring a BIPV system with a large inverter in Spain, it was observed that during cloudy weather, the inverter did not switch on at all, and 100% of the daily insolation was wasted [Stamenic et al., 1999].

system, often integrated (with the module) in parts of the building which are not easily accessible. Therefore, monitoring the performance, identifying the faulty devices, and replacing them can prove to be more of a problem in large systems rather than smaller ones. That said, the majority of the AC-modules tested so far are reported to have demonstrated reliable operation, but it is regarded that more monitoring is still necessary to establish the long-term reliability throughout the lifetime of the module [Schoen, 2001].

6.3 Modelling BIPV Performance

There is currently available a range of design tools (computer programs) which can assist the designer to size and cost a PV installation when given its location, average solar irradiance, and PV cell type, but only a small number of them specially address building-integrated applications (most are designed for stand-alone PV installations) [Baker et al., 2000]. A study carried out in 1997 reviewed the PV design tools available to designers of BIPV systems and provided an evaluation of selected tools [ETSU, 1997]. All the 11 design tools evaluated were found to be suitable for preliminary design, while only 3 were applicable to BIPV systems, and 3 were suitable for outline technical design. Some shortfalls were found in all the assessed tools, and recommendations were made in a separate report as to improvements that should be seen [ETSU, 1998].

In order for computer modelling to provide a reasonably accurate prediction/estimation of the size and energy performance of a PV system, it needs to be based on realistic time-varying meteorological conditions. This is particularly important for integrating PVs into the built environment, where the existing constraints on space often mean that the positioning (tilt and orientation) of the PV array may not be optimum for energy production (Section 6.2.2.1). In some cases, the PV array may be even divided into differently tilted and oriented arrays. In other words, energy calculations based on average irradiance values at the site and the nominal power of the PV modules, as provided by the manufacturer, are liable to involve a significant margin of error. Models based on real time-varying climate data (incident irradiance, ambient temperature, and wind speed and direction), and building structure and their impact on the PV electrical characteristics, on the other hand, can allow a more accurate assessment of system performance. They can be used for obtaining detailed predictions/ visualizations of any shading (amount and frequency) and hence, aid in designing the string configuration of the PV array in order to minimize losses (due to shading), optimize the design, and assess its true technical and economical viability. As such, it may be possible to 'strike a balance' between PV energy generation and architectural design (i.e., attaining appreciable PV electric output from adequate tilt, azimuth, and array configuration without compromising building aesthetics or structural demands).

In this section, a PV system integrated into the envelope of an office model (the same model utilized in previous chapters for daylight modelling) is investigated. Using the daylight coefficient method, detailed in Chapter 3, hourly climate data is used to predict the irradiation incident on the office's vertical facade. Then, the PV system hourly output is calculated, and the effect of facade orientation on annual system production is examined.

The PV module selected for modelling in this study is the 85-Watt monocrystalline BP-585 module, whose physical and electrical characteristics are specified in Appendix B [BP Solar, 2002]. Because of its high efficiency, the manufacturer recommends this module as particularly suited for applications which need maximum energy generation from a limited array area. Applications include utility grid-connected residential and commercial roof systems, building facades, and traditional industrial and remote applications. Examples of recent commercial and residential projects in which this module was employed are:

- The canopies of approximately 200 of BP's service stations worldwide (2000).

- The south-facing walls, roof lights, and rooftops of the BedZED environmentally friendly housing development, Croydon, UK (2002).
- The rooftops of the Village Green housing community, California, USA (2000).
- The rooftops of the Amersfoort housing development, Holland (2000).
- The rooftop of the Technopark Business Centre, Zurich, Switzerland (1997).
- The south facade of the Northumberland Building at the University of Northumbria, Newcastle, UK (1995).

In order to predict the performance of a PV array and determine its output power at a particular instant in time, three main parameters are required. These parameters are as follows:

- The irradiation incident on the plane of the array.
- The module operating characteristics.
- The PV cell temperature inside the module.

The incident irradiation is calculated from the site meteorological data (as shown in the next section), and the module operating characteristics are determined from the electrical specifications obtained from the manufacturer. The cell temperature, however, is less straight-forward. In addition to the incident irradiation and module operating characteristics, the complex thermal environment that determines the cell temperature depends on several other factors. These include the ambient temperature, wind speed and direction, module design (front cover and backing sheet), module orientation, and mounting structure [King et al., 1998]. The cell temperature needs to be calculated using a thermal model as will be detailed in Section 6.3.2.

6.3.1 Predicting Incident Irradiation

The solar radiation which reaches the surface of the earth consists primarily of two components: direct, appearing to come straight from the sun, and diffuse, scattered by water vapour and dust in the atmosphere. For example, in north-western Europe, on average over the year, approximately 50% of the solar radiation is diffuse and 50% direct (for a horizontal surface) [Boyle, 1996]. The annual total solar radiation incident on a horizontal surface near the equator is over 2000 kWh/m^2, while in north-western Europe, it is approximately 1000 kWh/m^2. In the UK, on average in July, the solar radiation incident on a horizontal surface is approximately 5 kWh/m^2.day, while in January, it is approximately one-tenth of that value or less [Boyle, 1996].

The quantity and character (i.e., direct or diffuse) of the annual total irradiation available in Kew, UK is presented in the form of frequency histograms in Figure 6-6 (a visualization of the raw time-series was given in Figure 3-5). The Kew-84 TRY data (used previously in Chapter 3) contained the hourly diffuse horizontal and direct normal components of the solar radiation. The hourly sun position was computed from the geographical position and time stamp of the TRY, and then, the direct horizontal irradiation was calculated using the sun altitude as follows:

$$\text{Direct horizontal irradiance} = \text{Direct normal irradiance} \times \sin\ (\text{sun altitude})$$

The total/global hourly horizontal irradiation was obtained by summing the diffuse horizontal and the direct horizontal components.

Following the XDAPS formulation detailed in Section 3.2, a set of DCMs was calculated for a point on the vertical facade of the office model. Then, in a process similar to that in Section 3.3.3, the hourly irradiation incident on the facade was derived from the DCMs as 4 components of irradiation, i.e., direct and diffuse due to the sky and direct and diffuse due to the sun. The process was, in fact, slightly simpler than deriving illuminances since there was no need for the input irradiation values to be converted to illuminances

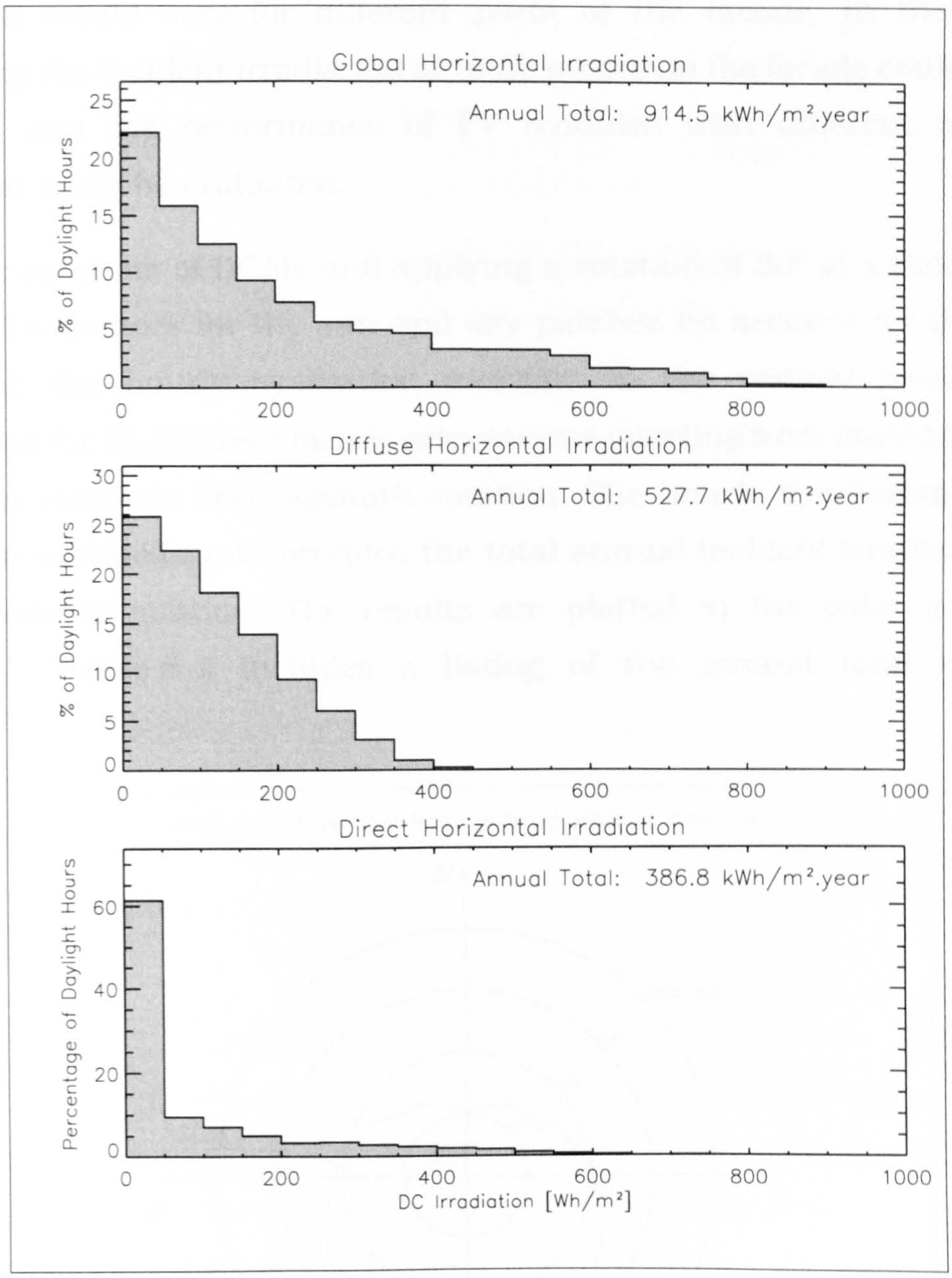

Figure 6-6 DC predicted irradiation on a horizontal surface in Kew, UK

using a value for luminous efficacy. The total hourly irradiation incident on the vertical facade was determined by the summation of the derived four components of irradiation.

Note that since this office model was unobstructed (i.e., there was no shading), any point on the facade could be chosen for the calculation of the incident irradiation. However, if there were obstructions around the office causing potential partial shading on the facade, then the incident irradiation would vary for different parts of the facade. In that case, calculating the incident irradiation at more points on the facade could easily be done, and the performance of PV modules with different incident irradiation could be evaluated.

Using the same set of DCMs and applying a rotation of 30° at a time to the generated radiances for the sun and sky patches (to account for different azimuths), the hourly irradiation incident on the vertical facade was determined for 12 different facade orientations (starting from north) in order to cover a complete 360° azimuth rotation. The hourly irradiation values were then summed up to produce the total annual incident irradiation for each facade orientation. The results are plotted in the polar graph of Figure 6-7. Table 6-2 includes a listing of the annual total incident

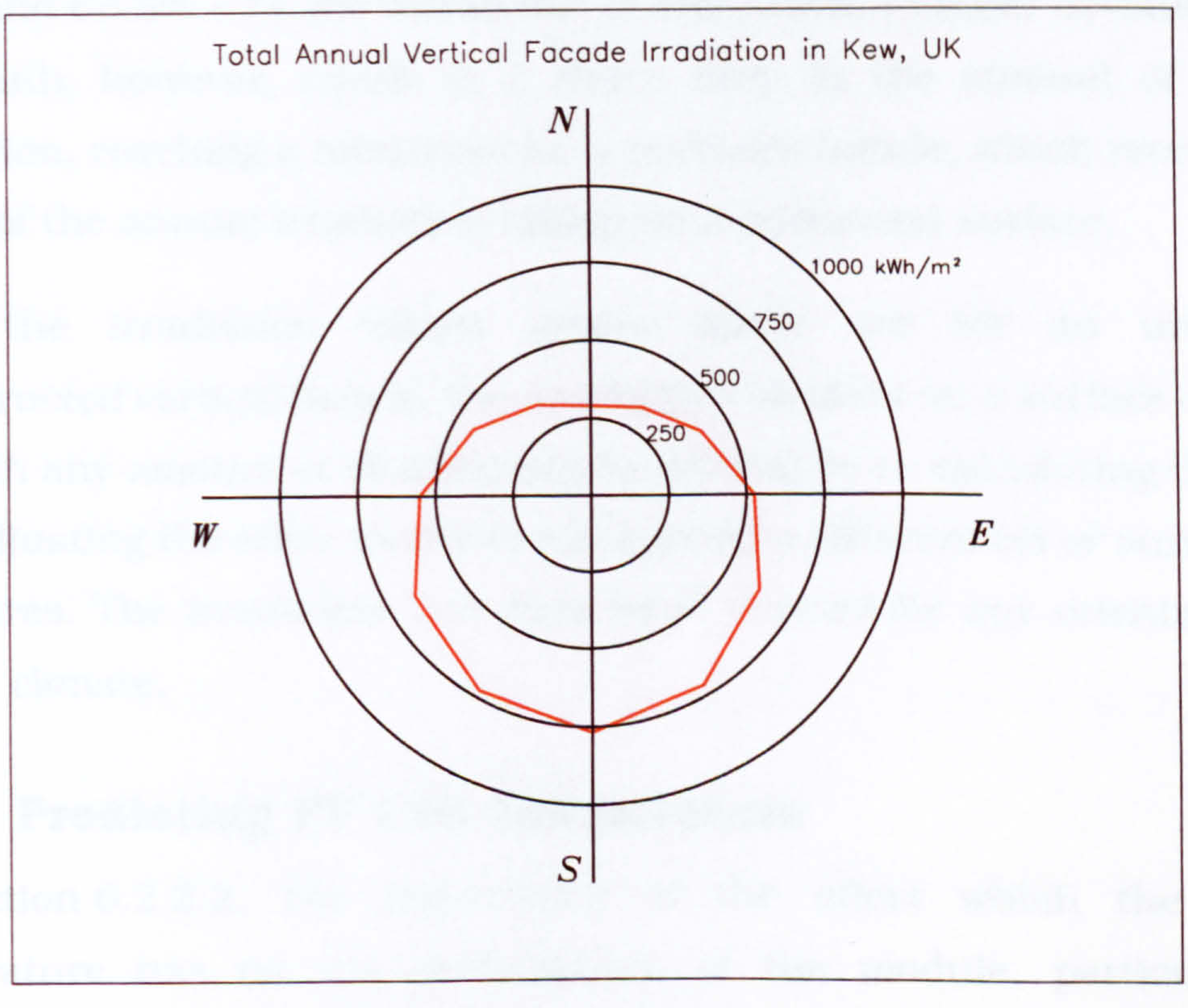

Figure 6-7 Total annual irradiation on an obstructed vertical facade

	kWh/m^2				
	Horizontal	North	East	South	West
Total annual incident irradiation	914.5	291.3	525.6	767.6	550.9

Table 6-2 The total annual irradiation in kWh/m^2 incident on the horizontal and on four unobstructed vertical facades

irradiation for the main four vertical facade orientations as well as that incident on a horizontal surface (for example, the roof).

Note that while a vertical facade facing due south, in this northern-hemisphere location, receives the largest amount of irradiation annually (83.9% of the irradiation on the horizontal) compared to other vertical orientations, slight deviations from due south are not very critical. If restrictions are encountered in an urban environment, and the PV system cannot be installed onto a facade facing exactly due south, it can still receive 78.4% - 79.6% of the horizontal irradiation within 30° either side of due south and 68.3% - 71.2% within 60° of due south. Further deviations from due south, however, result in a sharp drop in the amount of incident irradiation, reaching a minimum for a northern facade, which receives only 31.9% of the annual irradiation falling on a horizontal surface.

While the irradiation values shown above are for an unshaded/ unobstructed vertical facade, the irradiation incident on a surface of any tilt and with any amount of shading can be derived by re-calculating the DCMs after adjusting the office model to incorporate a different tilt or surrounding structures. The irradiation can then be re-derived for any orientation and for any climate.

6.3.2 Predicting PV Cell Temperature

In Section 6.2.2.2, the importance of the effect which the PV cell temperature has on the performance of the module, particularly for building-integrated systems, was discussed. In order to calculate the PV cell temperature, a number of thermal models characterized by different degrees of complexity were reviewed. It was deduced that while detailed models with extensive input and thermal calculations can provide higher accuracies, they would be specific to certain constructions, designs, and materials. Simpler thermal models, on the other hand, were considered more generic and hence applicable for calculations of most PV applications, as indicated by field results reported in the literature [Lorenzo et al., 1994][Wilshaw et al., 1996].

Therefore, in this study, the thermal model presented by Duffie et al. [Duffie et al., 1991] (detailed below) was adopted for calculating PV module temperature in the modelled system. Three more simple thermal models were also reviewed during the course of this study (described in Appendix C). However, since they were empirical models, there was concern that the constants used in the equations might be material and construction dependent.

According to Duffie et al.'s thermal model, the operation temperature of a PV module is determined by an energy balance [Duffie et al., 1991]. The solar energy that is absorbed by a module is converted partly into thermal energy and partly into electrical energy which is removed from the cell through the external circuit. The thermal energy must be dissipated by a combination of heat transfer mechanisms: the upward/front losses and the back losses. Back losses are usually considered to be more important in building-integrated PV applications since heat transfer from the module should be maximized so that the cells will operate at the lowest possible temperature.

An energy balance on a unit area of PV module, which is cooled by losses to the surroundings, can be defined as

$$\text{Absorbed energy} = \text{Electrical energy} + \text{Thermal energy}$$

$$\tau\alpha G_T = \eta_c G_T + U_L(T_c - T_a) \tag{6-1}$$

where

τ = Transmittance of the glass cover over the cells.

α = Fraction of the radiation incident on the surface of the cells that is absorbed.

G_T = Irradiance incident on the module (W/m^2).

η_c = Efficiency of the module in converting incident radiation into electrical energy. This efficiency will vary from zero to the maximum module efficiency, depending on how close to the maximum power point (MPP) the module is operating.

U_L = Loss coefficient including losses by convection and radiation from the module's top and bottom and by conduction through any mounting framework/structure that may be present, all to the ambient temperature, T_a (in K).

T_c = Cell/module temperature (K).

The nominal operating cell temperature (NOCT) is defined as the cell or module temperature, $T_{c,NOCT}$, that is reached when the cells are mounted in their usual way at a solar radiation level of 800 W/m^2, $G_{T,NOCT}$, a wind speed of 1 m/s, an ambient temperature of 20°C, $T_{a,NOCT}$, and no load operation (i.e., with $\eta_c = 0$). Measurements of the cell temperature, ambient temperature, and solar radiation at NOCT can be used in Eq 6-1 in order to determine the value of the ratio $\frac{\tau\alpha}{U_L}$ as follows:

$$\frac{\tau\alpha}{U_L} = \frac{(T_{c,NOCT} - T_{a,NOCT})}{G_{T,NOCT}} \tag{6-2}$$

In this thermal model, the term $\frac{\tau\alpha}{U_L}$ was assumed to be constant [Duffie et al., 1991], and so the module temperature at any other condition can then be found from Eq 6-1 as follows:

$$T_c = T_a + \left(G_T \frac{\tau\alpha}{U_L}\right)\left(1 - \frac{\eta_c}{\tau\alpha}\right) \tag{6-3}$$

It has been argued that an estimate of 0.9 for the term $\tau\alpha$ in Eq 6-3 can be used without serious error since the term $\frac{\eta_c}{\tau\alpha}$ is small compared to unity [Duffie et al., 1991].

The maximum power point efficiency of a module, η_{mpp}, is given by

$$\eta_{mpp} = \frac{I_{mpp}\, V_{mpp}}{A_c\, G_T} \qquad \textbf{(6-4)}$$

where

I_{mpp} = Current at maximum power point (A).

V_{mpp} = Voltage at maximum power point (V).

A_c = Area of the module (m^2).

The temperature dependence of the maximum power point efficiency, η_{mpp}, can be expressed in terms of a maximum power point efficiency temperature coefficient, $\mu_{\eta_{mpp}}$, as follows:

$$\eta_{mpp} = \eta_{mpp,\,STC} + \mu_{\eta_{mpp}}(T_c - T_{STC}) \qquad \textbf{(6-5)}$$

where

$\eta_{mpp,\,STC}$ = Maximum power point efficiency at standard test conditions (STC).

T_{STC} = Module temperature at STC (K); 25°C + 273 = 298 K.

The maximum power point efficiency is a linear function of temperature and for many modules, considered to be independent of solar radiation [Duffie et al., 1991]. The value of $\mu_{\eta_{mpp}}$ is generally a negative number since cell efficiency decreases with temperature. It can be determined by differentiating Eq 6-4 with respect to temperature as follows:

$$\mu_{\eta_{mpp}} = \frac{d\eta_{mpp}}{dT} = \left[I_{mpp}\frac{dV_{mpp}}{dT} + V_{mpp}\frac{dI_{mpp}}{dT}\right]\frac{1}{A_c\, G_T} \qquad \textbf{(6-6)}$$

Since the short circuit current temperature coefficient, $\mu_{I_{sc}}$ (A/K), is usually small, this indirectly results in $\frac{dI_{mpp}}{dT} \approx 0$ and $\frac{dV_{mpp}}{dT} \approx \frac{dV_{OC}}{dT}$.

The temperature coefficient of the maximum power point efficiency can, therefore, be approximated by the following equation:

$$\mu_{\eta_{mpp}} = \frac{I_{mpp}}{A_c\, G_T}\frac{dV_{OC}}{dT} = \frac{I_{mpp}}{A_c\, G_T}\mu_{V_{oc}} = \eta_{mpp,\, STC}\frac{\mu_{V_{oc}}}{V_{mpp}} \qquad \text{(6-7)}$$

where

$\mu_{V_{oc}}$ = Open circuit voltage temperature coefficient (V/K).

If the PV system contains an MPP tracker, operation is ensured to be as close to the MPP as possible, i.e., $\eta_c = \eta_{mpp}$, Eq 6-5 can be substituted in Eq 6-3 in order to obtain T_c as follows:

$$T_c = T_a + \left(G_T\frac{\tau\alpha}{U_L}\right)\left[1 - \frac{\eta_{mpp,\, STC} + \mu_{\eta_{mpp}}(T_c - T_{STC})}{\tau\alpha}\right] \qquad \text{(6-8)}$$

Re-arranging the parameters to isolate T_c on the left-hand side, the equation becomes

$$T_c = \frac{T_a + \left(G_T\frac{\tau\alpha}{U_L}\right)\left[1 - \frac{\eta_{mpp,\, STC} - \mu_{\eta_{mpp}} T_{STC}}{\tau\alpha}\right]}{1 + \left[\frac{\mu_{\eta_{mpp}} G_T}{\tau\alpha} \times \frac{\tau\alpha}{U_L}\right]} \qquad \text{(6-9)}$$

Substituting for the value of $\frac{\tau\alpha}{U_L}$ as calculated from Eq 6-2, $\tau\alpha = 0.9$, and $T_{STC} = 298$, Eq 6-9 can be solved for T_c as follows:

$$T_c = \frac{T_a + \left(G_T\frac{\tau\alpha}{U_L}\right)\left[1 - \frac{\eta_{mpp,\, STC} - (\mu_{\eta_{mpp}} \times 298)}{\tau\alpha}\right]}{1 + \left[\frac{\mu_{\eta_{mpp}} G_T}{0.9} \times \frac{\tau\alpha}{U_L}\right]} \qquad \text{(6-10)}$$

Eq 6-10 was utilized for calculating the hourly cell temperature of the modelled BIPV system, using as input the derived incident irradiance on the

PV facade, PV module specifications, and the hourly ambient temperature from the climate file.

6.3.3 Calculating Electric Output

In order to calculate the output current and voltage, and consequently, the PV output power, the simple model described below was formulated.

Since the current is directly proportional to the intensity of incident irradiance, and it increases (albeit slightly) as the cell/module temperature increases, then the operation current maintained at MPP, $I_{c,\,mpp}$, can be found using the following equation:

$$I_{c,\,mpp} = \left[\frac{I_{mpp}\,G_T}{G_{STC}}\right] + [\mu_{I_{sc}}\,(T_c - T_{STC})] \qquad \textbf{(6-11)}$$

where

G_{STC} = Reference irradiance, i.e., 1000 W/m^2 at STC.

Also, since the voltage is directly proportional to the logarithm of the incident irradiance [Duffie et al., 1991], and it decreases linearly with the rise in module temperature, then the operation voltage maintained at MPP, $V_{c,\,mpp}$, can be found using the following equation:

$$V_{c,\,mpp} = \left[\frac{V_{mpp}\,\log(G_T)}{\log(G_{STC})}\right] + [\mu_{V_{oc}}\,(T_c - T_{STC})] \qquad \textbf{(6-12)}$$

where $\mu_{V_{oc}}$, the temperature coefficient of the open circuit voltage (V/K), is generally a negative value.

The output power at MPP operation, $P_{c,\,mpp}$, can, therefore, be calculated from the product of the operation current and voltage, i.e.,

$$P_{c,\,mpp} = I_{c,\,mpp} \times V_{c,\,mpp} \qquad \textbf{(6-13)}$$

The operation efficiency, $\eta_{c,\,mpp}$, can also be calculated as follows:

$$\eta_{c,mpp} = \frac{P_{c,mpp}}{A_c\,G_T} \tag{6-14}$$

6.3.3.1 System DC Output

To calculate the electric output from a PV array, the module voltage should be multiplied by the number of modules connected in series (forming a string), and the current should be multiplied by the number of strings connected in parallel. The product of the resulting voltage and current gives the array output.

The array output should be further adjusted by using two additional terms to account for soiling losses, L_S, and modules mismatch losses, L_M. The soiling losses will vary throughout the year, but studies have shown them to be approximately 3% for modules on at least a 40° tilt, while the mismatch parameter is approximated to 3% [Kroposki et al., 1999]. These losses can be incorporated as follows to calculate the adjusted power, $P_{adj,DC}$.:

$$P_{adj,DC} = P_{DC} \times (1.0 - (L_S + L_M)) \tag{6-15}$$

$$P_{adj,DC} = P_{DC} \times (1.0 - (0.03 + 0.03)) \tag{6-16}$$

$$P_{adj,DC} = P_{DC} \times 0.94 \tag{6-17}$$

6.3.3.2 System AC Output

If the PV DC output is not to be used for DC loads or load management equipment (if present in the building), it is connected to the AC building grid with a single central inverter or multiple string inverters. The following simple model was introduced by Kroposki et al. for calculating the AC output for grid-connected PV systems that use inverters with good maximum power point tracking abilities [Kroposki et al., 1999]. If a single central inverter is used, the array DC output is the one used in the calculation, but more commonly, smaller distributed inverters are used for the strings, in which case, individual string DC outputs are entered separately into inverters.

First, the inverter efficiency, η_{inv}, is calculated using the inverter characteristics (usually provided by the manufacturer) as follows:

$$\eta_{inv} = 1.0 - \left(\frac{P_{TO}}{P_{adj,DC}}\right) - (1.0 - \eta_{inv,mpp}) \times \left(\frac{P_{adj,DC}}{P_{inv,mpp}}\right) \quad \textbf{(6-18)}$$

where

P_{TO} = Inverter switch on power, i.e., minimum input power to the inverter required before it starts working (W), which is typically 1 - 5% of the inverter's rated power [Kroposki et al., 1999].

$\eta_{inv,mpp}$ = Inverter efficiency at maximum power point.

$P_{inv,mpp}$ = Maximum rated power of the inverter (W).

The AC power, P_{AC}, is then determined using the following equation:

$$P_{AC} = P_{adj,DC} \times \eta_{inv} \quad \textbf{(6-19)}$$

It should be noted that when sizing the inverter for a PV system, a good system design should ensure that the PV system generates the main fraction of its annual DC energy without reaching the rated power of the inverter [Nofuentes et al., 1999]. This means that the inverter is overloaded only for negligible fractions of time.

The equations detailed above were coded into new XDAPS routines for predicting the hourly PV output based on the derived incident irradiance on the PV facade, the calculated hourly cell temperature, and the module electric characteristics, as discussed below.

6.3.4 BIPV in the Office Model

Using the same office model used in the previous chapters for daylight illuminance modelling, a PV array was modelled as occupying the non-glazed part of the facade (i.e., below the window), as shown in Figure 6-8. It was assumed that the PV array integrated into the office model was maximum power point tracked, i.e., the voltage of the array was

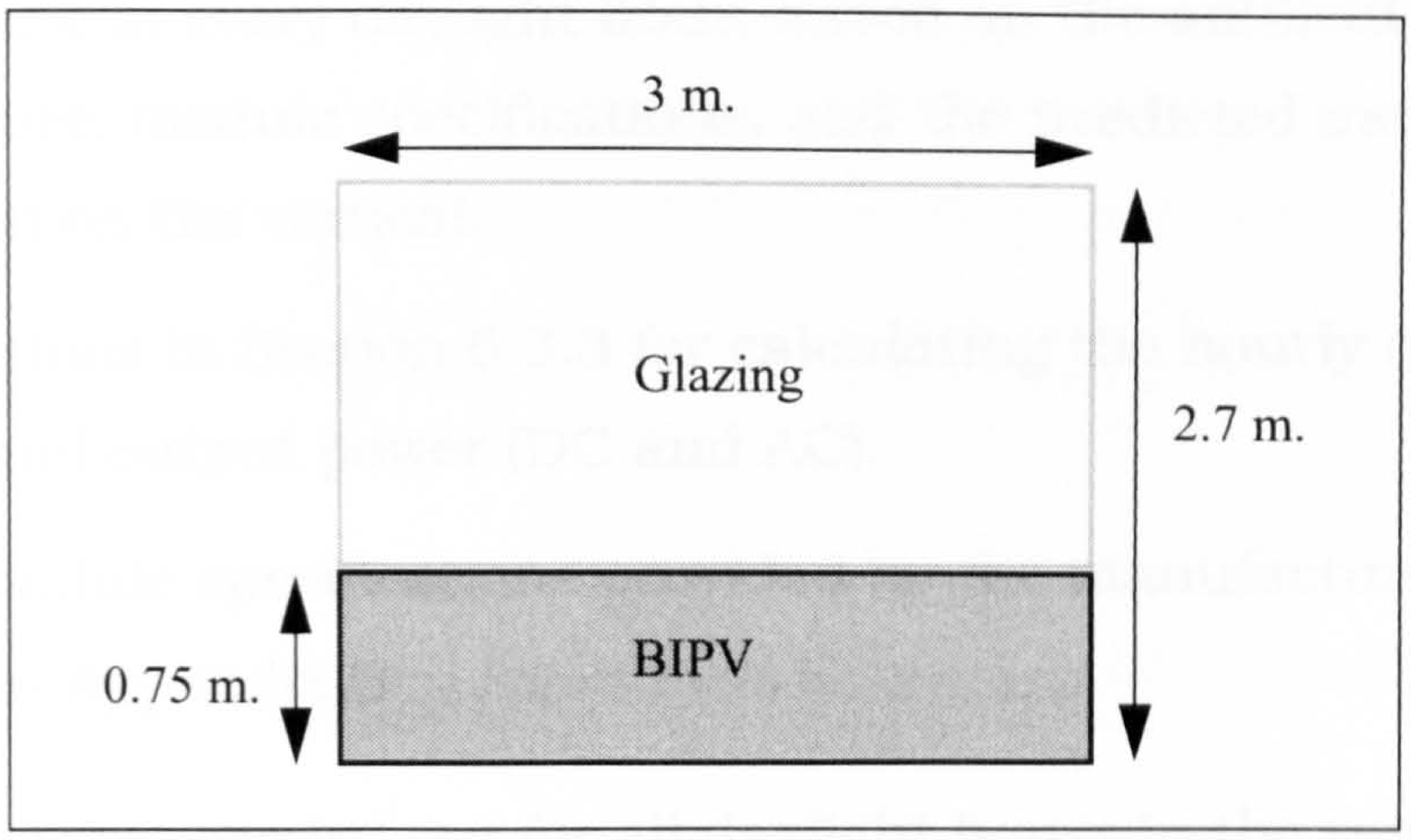

Figure 6-8 PV array integrated into the office facade below the window

continuously adjusted such that the power produced was a maximum, and that it was grid-connected through a DC-to-AC inverter. It was also assumed that the PV array was passively cooled, i.e., the heat sink for the thermal energy precipitated in the array was the ambient environment.

Since only part of a whole PV array (for the whole facade) was modelled, proper sizing of the inverter (or several string inverters) was not appropriate. Hence, for the DC-to-AC conversion of the electric output in this model, total losses in the balance of the system were taken as a typical value of approximately 15% [CIBSE, 2000]. This was to include inverter losses as well as wiring and mismatch losses. Note that losses due to temperature effects are already included in the thermal model for calculating the module temperature.

Therefore, the electric output per m^2 of the PV-covered facade area was calculated using the following:

- The hourly incident irradiation predicted in Section 6.3.1 for 12 vertical facade orientations (4316 daylight hours for each) based on hourly horizontal irradiation from the climate file.

- The thermal model described in Section 6.3.2 for estimating module temperature at every daylight hour, based on the ambient temperature, module specifications, and the predicted incident irradiation on the vertical.
- The equations in Section 6.3.3 for calculating the hourly current, voltage, and output power (DC and AC).
- The PV module specifications provided by the manufacturer as detailed in Appendix B.

The calculation was carried out for all daylight hours in the year and for 12 azimuth orientations, starting from north and incrementing clockwise by 30° at a time in order to cover a complete 360° azimuth rotation. The results were then summed up for each facade orientation to produce annual electric energy output. This is shown in Figure 6-9, and a listing of the results for

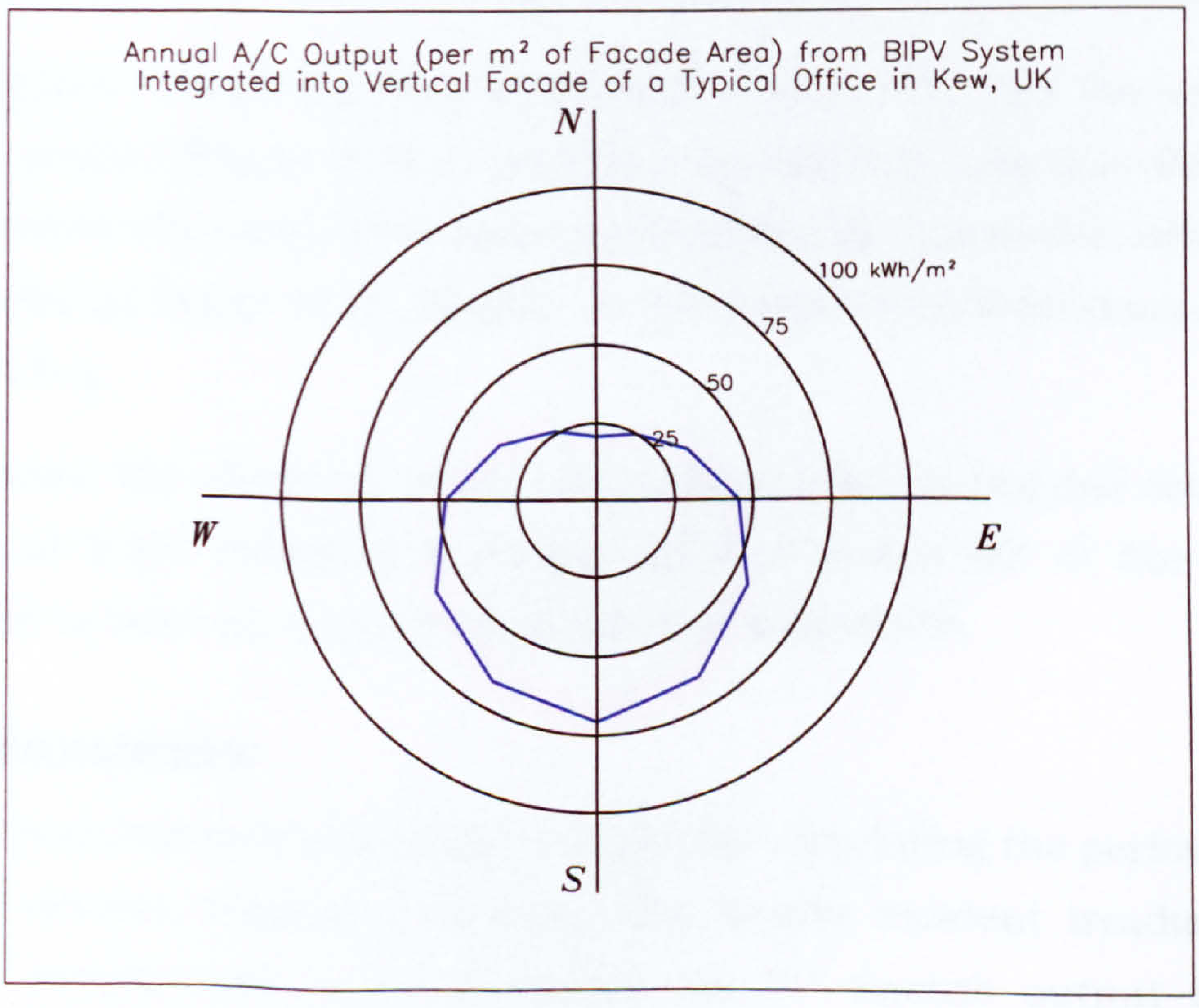

Figure 6-9 Total annual energy output (A/C) from a PV array integrated into a vertical facade

the main four azimuth orientations is shown in Table 6-3. The total annual

	kWh/m^2				
	Horizontal	North	East	South	West
BIPV Electric Output	85.3	20.7	45.5	70.7	47.9

Table 6-3 Total annual energy output (A/C) in kWh/m^2 of facade area covered with BIPV compared to that output from a horizontal BIPV system

electric energy produced by a horizontal PV system was also included in the table for comparison.

While due south is clearly the optimum vertical orientation for this northern-hemisphere locale, deviation to south east or south west would still produce 85.7% - 88.6% of the south facade's output. Any further rotation from due south, however, would result in a much bigger drop in output, with the minimum occurring for a facade facing due north, which produces only 29.3% of the energy expected from a south-facing facade.

Knowing the annual incident irradiation (Figure 6-7) and the annual PV electric output (Figure 6-9), it was then possible to calculate the annual BIPV system efficiency. This was computed for all 12 azimuth orientations and plotted in Figure 6-10. Results for the main four orientations are listed in Table 6-4.

As expected, the efficiency of the BIPV system when facing due south is the highest at 9.2%. However, a system oriented within 60° of due south is predicted to have an annual efficiency of at least 8.9%.

6.4 Summary

The method demonstrated in this chapter for simulating the performance of a BIPV system, through predicting the hourly incident irradiation and module temperature and calculating the PV electric output based on realistic time-varying climate data, provides a simple accurate tool which can be used to assess the performance of most PV systems integrated into

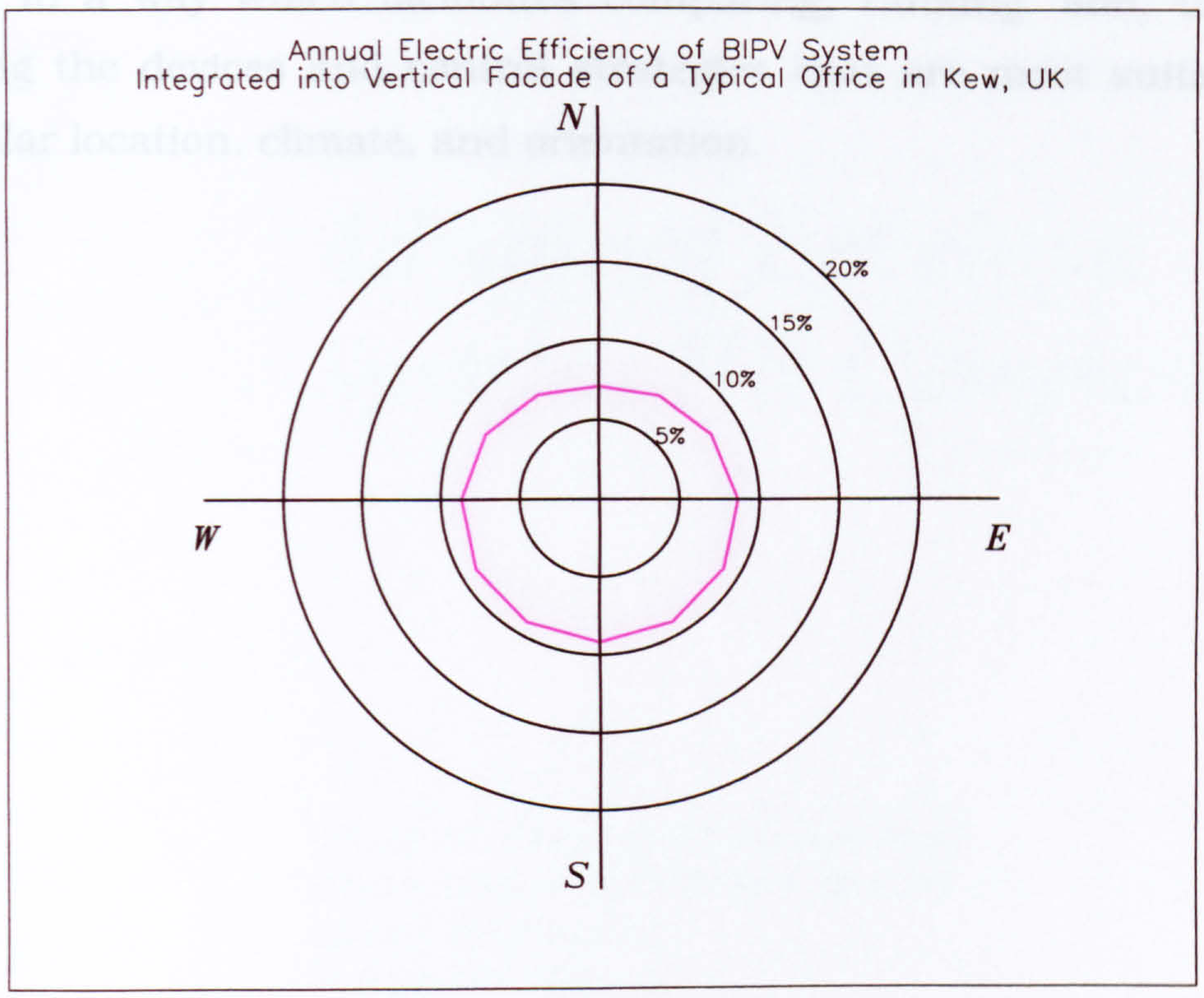

Figure 6-10 Annual BIPV system efficiency

	Horizontal	North	East	South	West
BIPV system efficiency	9.3%	7.1%	8.7%	9.2%	8.7%

Table 6-4 Annual BIPV system efficiency for vertical facades and a horizontal surface

buildings with any tilt and orientation and at any location. Building designers and developers may find this useful in realistically quantifying the potential contribution of electricity generated by BIPVs to reducing the net primary energy consumption of buildings, and hence, assisting in evaluating the cost-effectiveness of BIPV systems.

The results from this chapter and the previous chapters, related to daylight illumination and electric lighting energy consumption by lighting controls which are associated with the operation of switchable window devices, are all combined and expanded upon in the following chapter. The applicability of the proposed models and analysis metrics is examined in locations of different climatic conditions. The predicted illuminance and energy results relating to the different envelope systems are processed and displayed/ plotted in a way which facilitates comparing, ranking, and, ultimately, selecting the devices and control strategies that are most suitable for a particular location, climate, and orientation.

Chapter 7

Advanced Envelope Systems III: Comparison

"There was a young lady named Bright,
Whose speed was far faster than light;
She set out one day
In a relative way
And returned on the previous night."

ARTHUR BULLER 1874-1944 (*'RELATIVITY'* IN *PUNCH*, 19 DECEMBER, 1923)

In Chapter 4, a new metric for quantifying the usefulness as well as the availability of daylight in office interiors based on real time-varying climatic conditions was presented. In Chapter 5, this metric was used for assessing the impact and optimizing the performance of switchable window devices (such as automated blinds and electrochromic glazing) with respect to internal illumination in office buildings. The corresponding electric energy required for artificial lighting was also determined using scenarios coupling the operation of these switchable devices with daylight-linked lighting controls. In Chapter 6, a model was developed in order to accurately compute the electric output from a PV system when integrated into the vertical facade of an office, based on real time-varying climatic conditions.

7.1 'Strategic' Modelling Approach

In this chapter, the custom-written routines (developed in previous chapters) which simulate the performance of the different envelope systems (integrated into the transparent and opaque areas of a building envelope) are combined to form an automated modelling and analysis tool. The input to this tool is the raw climate data for any location, and the output is the daylight illumination and/or energy performance results relating to the required envelope system and control strategy for any given office design, as shown below.

7.1.1 Climate Zones

In addition to the climate data for Kew, UK, which was used previously in this study to model the daylight illuminance and energy consumption, 13 more locations worldwide were selected for investigation in this chapter. Since there is currently an abundance of hourly irradiation and ambient temperature data, which is recorded at weather stations around the world and which is readily 'downloadable' from the Internet, this was regarded as a good opportunity to test the applicability of the developed models and analysis metrics and the validity of the different envelope systems in a variety of climates and locations. The locations, marked on the map in Figure 7-1, were considered to represent a wide range of climatic conditions at different latitudes and in both hemispheres. The location names and their longitudes and latitudes are listed in Table 7-1.

As mentioned in Chapter 3, the mixing function for the sky blend model in the XDAPS formulation had been tuned and proven valid for typical UK skies. There is, however, no compelling reason why the sky blend approach should not be suitable for other locales, i.e., the approach is generally still valid for locales further afield. Nonetheless, tuning the sky mixing function requires values for the illuminance incident on the main four vertical orientations. While these data measurements were part of the dataset from the BRE-IDMP sky monitoring study, which was used by Mardaljevic for

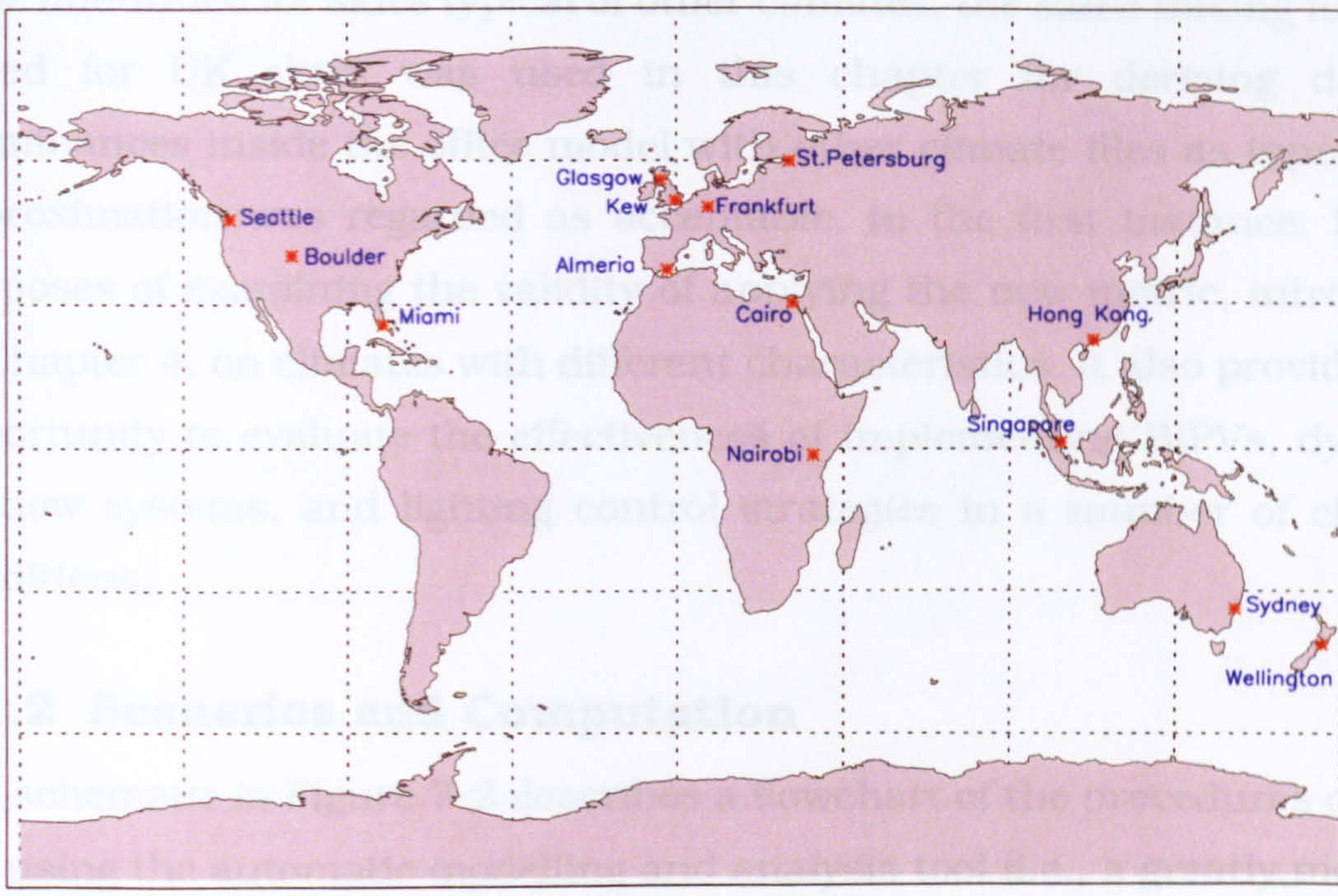

Figure 7-1 Locations of evaluated climates

Location	Latitude	Longitude	No. of Daylight Hours
Almeria, Spain	36.83°N	2.45°W	4278
Boulder, USA	40.02°N	105.25°W	4385
Cairo, Egypt	30.05°N	31.25°E	4271
Frankfurt, Germany	50.03°N	8.55°E	4350
Glasgow, UK	55.87°N	4.43°W	4166
Hong Kong, China	22.30°N	112.40°E	4204
Kew, UK	51.47°N	0.28°W	4316
Miami, USA	25.80°N	80.27°W	4361
Nairobi, Kenya	1.28°S	36.82°E	4380
Seattle, USA	47.45°N	122.30°W	4372
Singapore, Singapore	1.30°N	103.80°E	4127
St.Petersburg, Russia	59.92°N	30.25°E	4343
Sydney, Australia	33.90°S	151.20°E	3984
Wellington, New Zealand	41.30°S	174.78°E	4363

Table 7-1 Longitudes and latitudes of locations of studied weather files and numbers of corresponding daylight hours

validating the XDAPS formulation, such data was not available for the locales evaluated. Therefore, while ideally, the mixing function would need to be fine-tuned for skies typical of other climates, the same mixing function tuned for UK skies was used in this chapter for deriving daylight illuminances inside the office model with other climate files as input. This approximation was regarded as acceptable, in the first instance, for the purposes of examining the validity of applying the new metric, introduced in Chapter 4, on climates with different characteristics. It also provided the opportunity to evaluate the effectiveness of implementing BIPVs, dynamic window systems, and lighting control strategies in a number of climatic conditions.

7.1.2 Scenarios and Computation

The schematic in Figure 7-2 describes a flowchart of the procedures carried out using the automatic modelling and analysis tool (i.e., a greatly modified version of XDAPS). The same set of daylight coefficients calculated for the 12 calculation points (on the workplane) for the office model (Chapter 3) were used again. However, as discussed earlier, if any significant modifications to the office design were required, the DCMs would be re-calculated.

The hourly solar irradiation (global horizontal and direct normal) and ambient temperature data from Typical Meteorological Year (TMY) weather files for all 13 locations (+ Kew TRY) were 'loaded'. Similar to the steps described in Section 3.3.3, the number of daylight hours at each location, i.e., where the irradiation is greater than zero, was first calculated (they are listed in Table 7-1). For every daylight hour in the year at every geographical location, the sky (and sun) luminance and radiance distributions were generated for 12 azimuth orientations of the office model. These orientations started from north and incremented clockwise by 30° at a time in order to cover a complete 360° azimuth rotation. Note that, in principle, any number of possible orientations can be studied using the XDAPS formulation. Then,

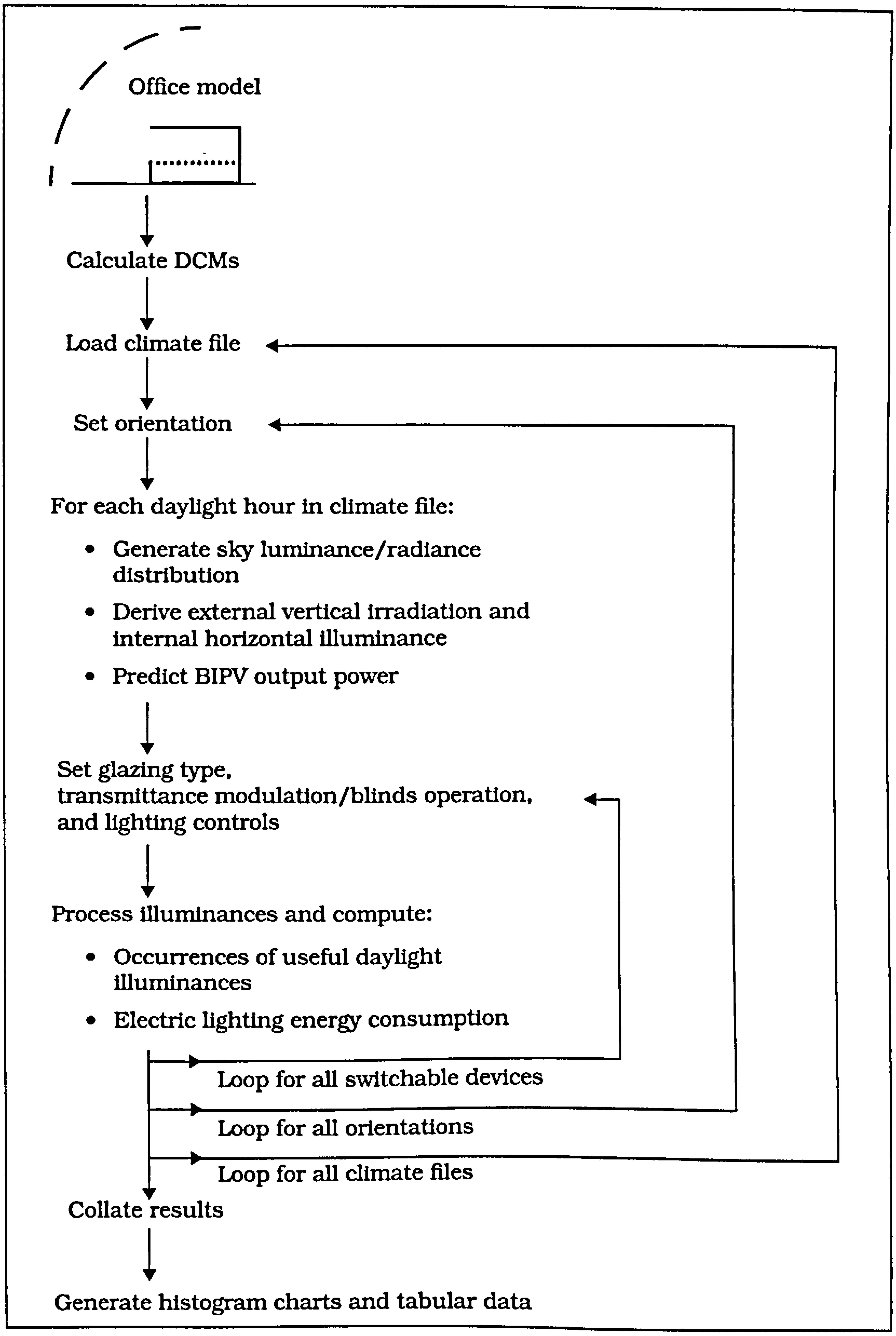

Figure 7-2 Outline of procedures

the external vertical irradiance (on the office facade) and the internal horizontal illuminance (at the 12 calculation points) were derived.

Note that the data values obtained were a total of '4 (components of illuminance derived from DCs) x 4300 (average number of daylight hours) x 12 (calculation points on the workplane) x 12 (orientations) x 14 (climate files)', i.e., ~34.7 million illuminance values. Similarly, there were '4 (components of irradiance derived from DCs) x 4300 (average number of daylight hours) x 1 (calculation point on the facade) x 12 (orientations) x 14 (climate files)', i.e., ~2.9 million irradiance values. In total over 37.6 million data values could be derived in almost real-time from one set of calculated daylight coefficients. This demonstrates the tremendous efficiency of the daylight coefficient approach as implemented in XDAPS.

Using the ambient temperature data, the predicted external vertical irradiance, and the PV module characteristics (specified in Appendix B), the BIPV output power was estimated for each daylight hour, orientation, and location. Note that alternative types of PV modules could be easily substituted for the module used.

The predicted hourly internal illuminance values were modulated according to the scenarios outlined in Figure 7-3 in order to mimic the effect of tinted glazing (medium and heavy tint as well as clear), shading devices (manual and automatic) and the full range of possible transmittance values for EC glazing (with linear and non-linear control). Then, the electric lighting energy consumption associated with the operation of daylight-linked lighting controls (on/off switching and continuous dimming) were also calculated. Note that again the above was computed for each daylight hour, orientation, and location. Note also that only the combinations of window devices and lighting controls that were considered practical/reasonable were modelled (Figure 7-3). The results obtained from this massive, largely automated, simulation exercise are plotted and discussed in the following sections.

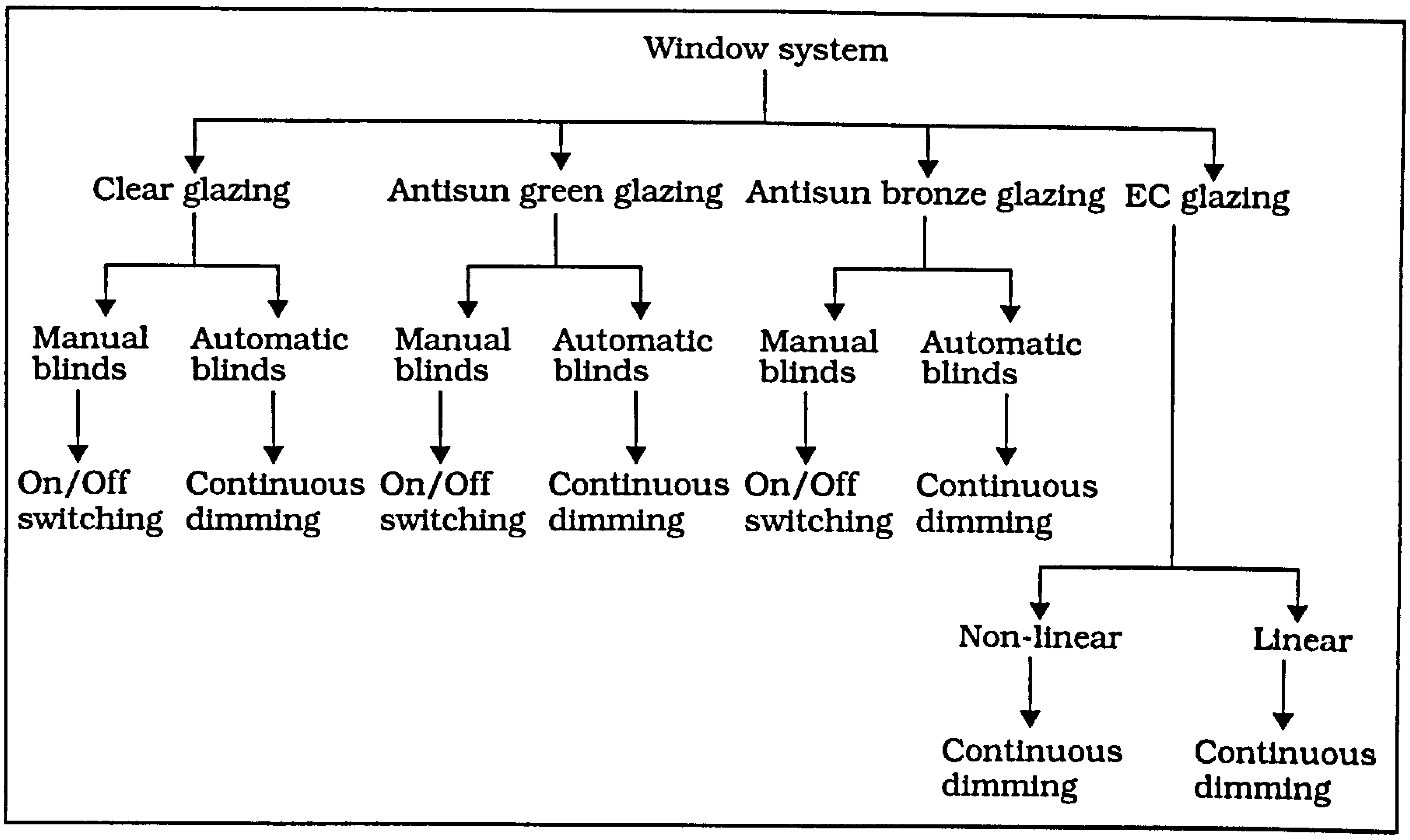

Figure 7-3 Schematic of window elements and associated electric lighting controls

7.2 Results I: Useful Daylight Illuminances

7.2.1 Unshaded Glazing and EC Glazing

Similar to the process described in Section 4.2.2, the predicted hourly daylight illuminance values for all the locations and all the office workplane calculation points were processed, and the percentages of the working year (i.e., $\frac{\text{Number of hours} \times 100\%}{3650}$) when the core length of the office receives useful daylight illuminances were computed for all 12 azimuth orientations. Due to the huge volume of data produced, only the results for the main four azimuth orientations are shown as bar charts in Figure 7-4. The figure contains useful daylight illuminance results for an unshaded window of clear double glazing (transmittance 0.76), antisun green (transmittance 0.63), antisun bronze (transmittance 0.44), and EC glazing (transmittance range 0.1 - 0.8) with linear and non-linear controls (according to the methods detailed in Chapter 5). The results are tabulated in Appendix D.

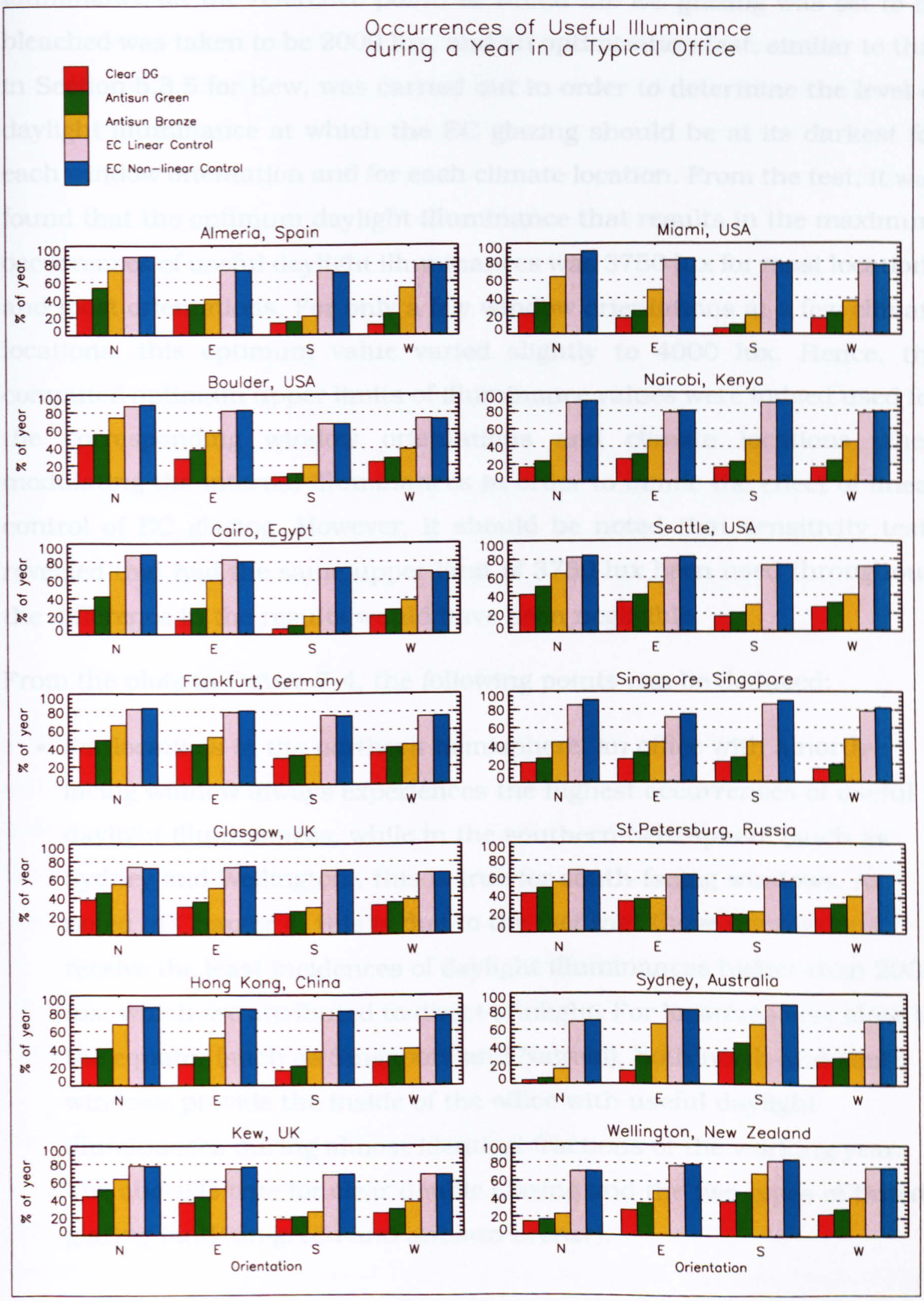

Figure 7-4 Occurrences of useful daylight illuminances with unshaded clear, tinted, and EC glazing in different locations around the world

Note that for linear control of EC transmittance, the value of daylight illuminance (at the reference point) at which the EC glazing was set to be bleached was taken to be 2000 lux, and an optimization test, similar to that in Section 5.3.5 for Kew, was carried out in order to determine the level of daylight illuminance at which the EC glazing should be at its darkest for each window orientation and for each climate location. From the test, it was found that the optimum daylight illuminance that results in the maximum occurrences of useful daylight illuminances was 3750 lux for most locations and most orientations. For only a few window orientations at a few climate locations, this optimum value varied slightly to 4000 lux. Hence, the computed optimum upper limits of illuminance values were indeed used for the corresponding window orientations and climate locations when modulating the internal illuminances in order to mimic the effect of linear control of EC glazing. However, it should be noted that sensitivity tests revealed that had the same upper limit of 3750 lux been used throughout, the difference in the results would have been negligible.

From the plots in Figure 7-4, the following points can be deduced:

- For locations in the northern hemisphere, an office with a north-facing window always experiences the highest occurrences of useful daylight illuminances, while in the southern hemisphere (such as Sydney and Wellington), this is true for south-facing windows. As noted in Chapter 4, this is due to the fact that those orientations receive the least incidences of daylight illuminances higher than 2000 lux, which are attributed to direct sunlight. For locations very close to the equator (such as Singapore and Nairobi), both north and south windows provide the inside of the office with useful daylight illuminances during almost identical fractions of the working year. The above is true for clear double glazing and the two types of tinted glazing (antisun green and antisun bronze).

- For all locations in both hemispheres and for all window orientations, using double glazing of lower transmittance, such as antisun green or antisun bronze, produces more occurrences of useful daylight illuminances than clear glazing. Since a lower glazing transmittance results in lower levels of daylight illuminances inside the office, then during more hours in the working year, daylight illuminances in the core length of the office will more likely fall under 2000 lux and into the useful range.
- EC glazing of either linear or non-linear control results in useful daylight illuminances occurring most of the working year at all locations and for all window orientations. While the results differ slightly by orientation, the differences are much less pronounced than in the case of clear or tinted glazings. In addition, as noted in Chapter 5, employing either of the control strategies for modulating the transmittance of the EC glazing results in almost the same number of hours in the working year during which daylight illuminances are in the useful range.

While the effect of EC glazing on the availability of useful daylight illuminances in the office distinctly surpasses the performance of the other examined types of glazing, as agreed earlier, unshaded windows, clear or tinted, are not practical. Shading devices are almost always installed on windows, and they are operated manually or automatically when discomfort is experienced by the occupants due to inconveniently high daylight illuminances. Hence, useful daylight illuminance results associated with the operation of blinds are examined in the following sections.

7.2.2 Manual Blinds and EC Glazing

The simple shutter model, which acted as a neutral density filter reducing daylight transmission by 80% (Section 5.1.2), was again used to simulate the ideal manual operation of Venetian blinds by the office occupants, i.e., drawn whenever the daylight illuminance predicted at any point on the office's workplane might be considered to cause discomfort and retracted when illuminance is required and there is no discomfort experienced.

Similar to Section 5.1.2, but now for all climate locations, the shutter was triggered if the daylight illuminance at any of the 12 calculation points in the office exceeds the threshold value of 2000 lux during office hours, reducing the internal illuminances at all the points for that hour by 80%. Otherwise, it was fully retracted. Then, the percentages of the working year when the core length of the office model receives useful daylight illuminances were calculated for the 12 azimuth orientations. The results for the main four azimuth orientations are plotted in the form of bar charts in Figure 7-5 and are tabulated in Appendix D. The results associated with EC glazing of linear and non-linear control are also included in the figure to facilitate comparison.

From the plots, the following points can be observed:

- With the operation of manual blinds, it is no longer the case that north-facing windows in the northern hemisphere and south-facing windows in the southern hemisphere provide the office with the highest occurrences of useful daylight illuminances. In fact, the differences in performance between the different azimuth orientations are, in this case, less pronounced than for unshaded windows, particularly for clear double glazing.
- In contrast to unshaded glazing, for all locations in both hemispheres and for all azimuth orientations, using manual blinds on windows with tinted glazing, i.e., of lower transmittance (antisun green or antisun bronze), produces less occurrences of useful daylight illuminances than clear glazing.
- Apart from north-facing windows in a few locations of high latitudes such as Kew (51.47°N), Glasgow (55.87°N), and St. Petersburg (59.92°N), the occurrences of useful daylight illuminances in the core length of the office increase for all locations and orientations with the

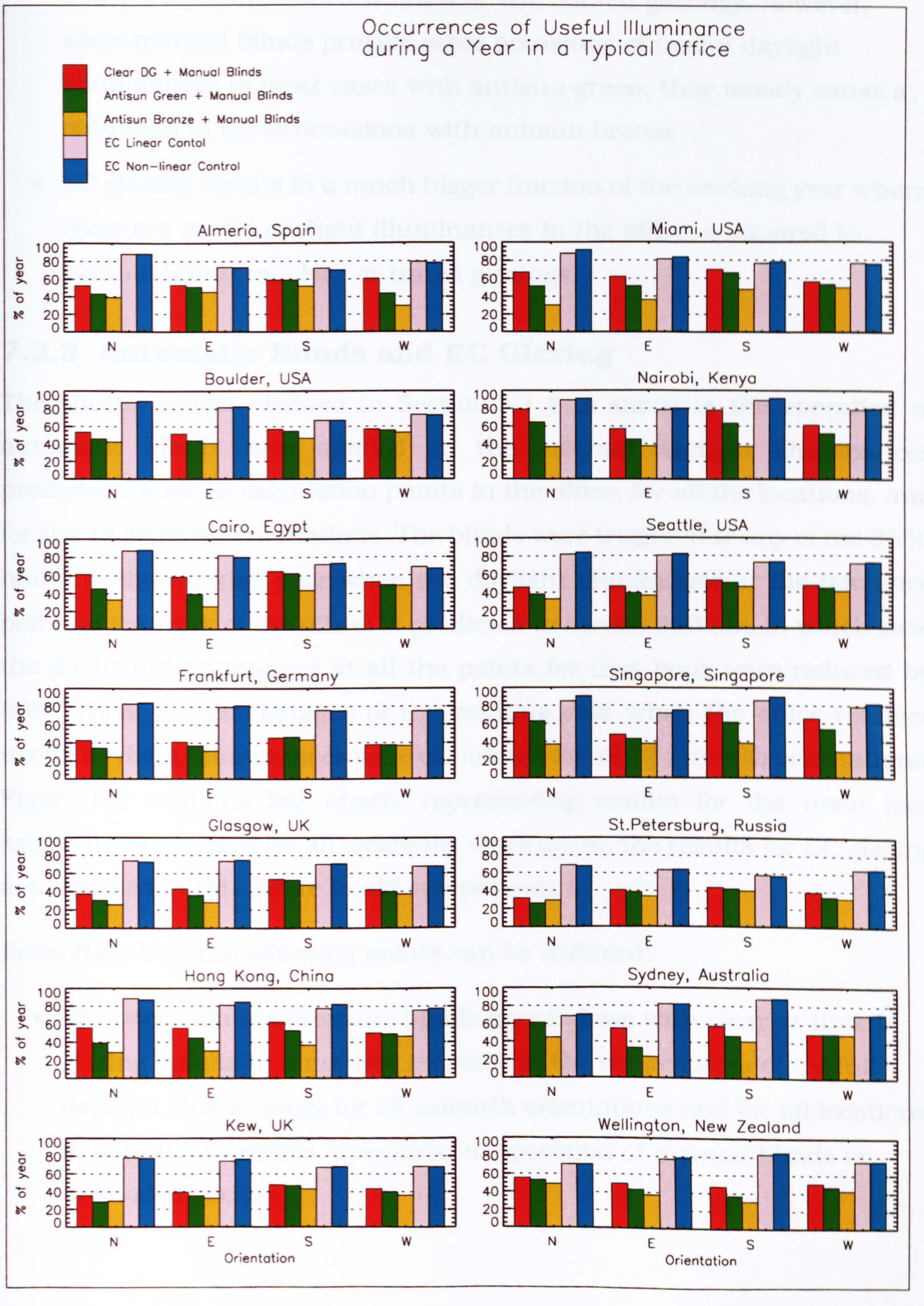

Figure 7-5 Occurrences of useful daylight illuminances with manual blinds on clear and tinted glazings and with EC glazing in different locations around the world

manual operation of blinds on windows with clear double glazing (compared to unshaded windows). With tinted glazings, however, while manual blinds provide more occasions of useful daylight illuminances in most cases with antisun green, they mostly cause a reduction in those occasions with antisun bronze.

- EC glazing results in a much bigger fraction of the working year where there are useful daylight illuminances in the office, compared to manual blinds on clear or tinted glazings.

7.2.3 Automatic Blinds and EC Glazing

The shutter model, defined in Section 5.1.4 to simulate the operation of automatic blinds, was applied on the internal daylight illuminances predicted for all 12 calculation points in the office, for all the locations, and for the 12 azimuth orientations. The blinds were triggered at any of the 3650 hours in the working year when the daylight illuminance at the reference point (at the back of the office) is predicted to exceed 500 lux, in which case the daylight illuminances at all the points for that hour were reduced by 80%. Then, the percentages of the working year when the office receives useful daylight illuminances were calculated for all 12 azimuth orientations. Figure 7-6 contains bar charts representing results for the main four azimuth orientations for all locations. Once again, the results for EC glazing are repeated in this figure to aid comparison.

From the plots, the following points can be deduced:

- The operation of automatic blinds on windows with clear or tinted glazing results in a marked increase in the occurrences of useful daylight illuminances for all azimuth orientations and for all locations in both hemispheres, compared to operation of manual blinds or unshaded glazing.

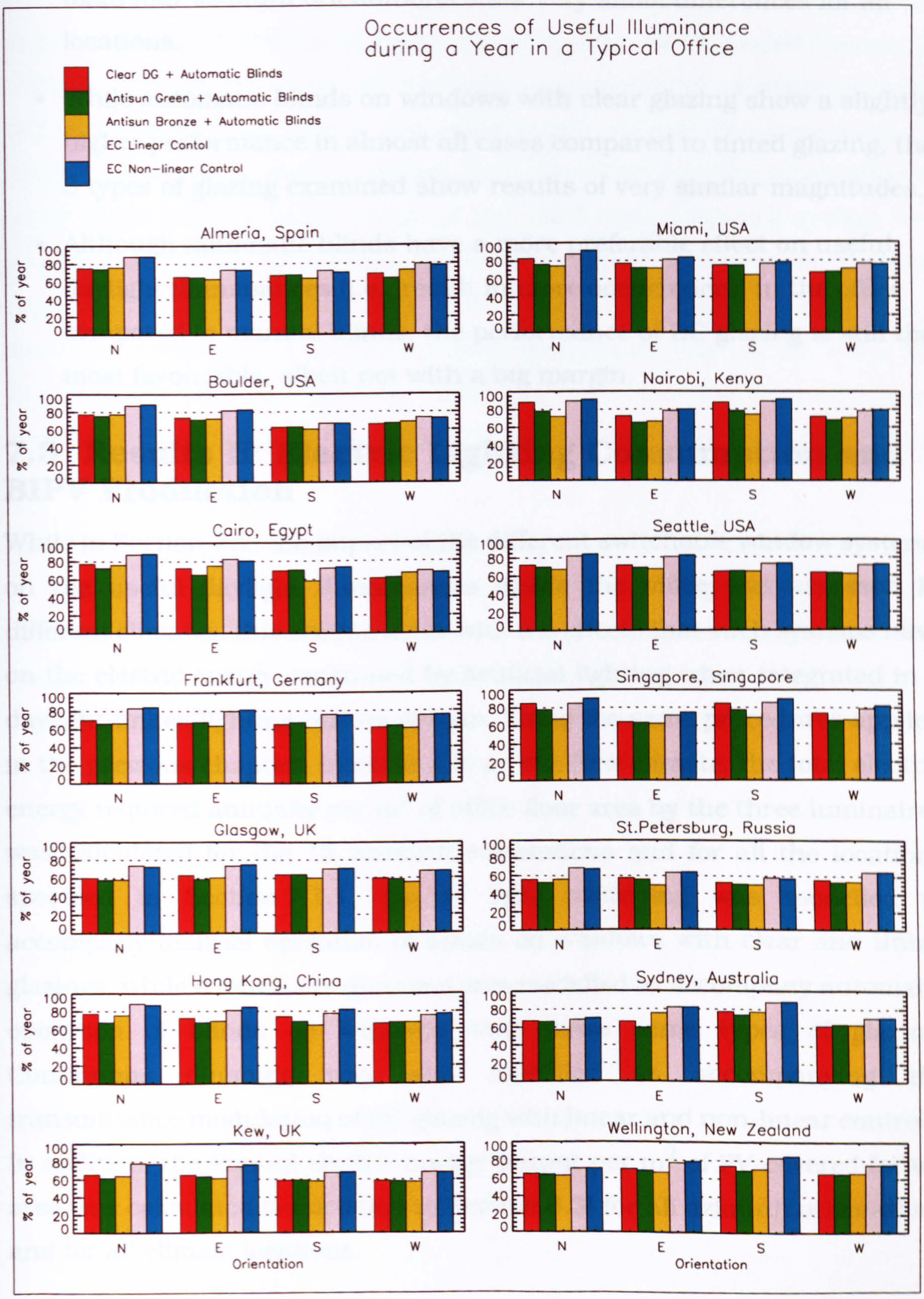

Figure 7-6 Occurrences of useful daylight illuminances with automatic blinds and with EC glazing in different locations around the world

- The availabilities of useful daylight illuminances attributed to the main four azimuth orientations show very small differences for all locations.
- While automatic blinds on windows with clear glazing show a slightly higher performance in almost all cases compared to tinted glazing, the 3 types of glazing examined show results of very similar magnitudes.
- Although automatic blinds have a more preferable effect on useful daylight illuminances (i.e., result in more occurrences) in the office compared to manual blinds, the performance of EC glazing is still the most favourable, albeit not with a big margin.

7.3 Results II: Electric Lighting Consumption and BIPV Production

While in Section 7.2, the impact of the different switchable window systems on the useful daylight illuminances inside the office was assessed in different climates, this section deals with the effects that such systems have on the electric energy consumed by artificial lighting when integrated in a daylight-linked lighting control system. Using the same procedures applied in the previous chapters (Section 4.3) on the Kew climate, the total electric energy required annually per m^2 of office floor area by the three luminaires was calculated for the 12 azimuth orientations and for all the locations specified in Section 7.1.1. On/off light switching was modelled to accompany manual operation of blinds on windows with clear and tinted glazings, while continuous dimming was modelled to accompany automatic operation of blinds on windows with those same types of glazing. Continuous dimming was also modelled as accompanying the transmittance modulation of EC glazing with linear and non-linear controls. In addition, the annual electric energy output per m^2 of PV-covered facade area was calculated (as detailed in Section 6.3) for all azimuth orientations and for all climate locations.

Note that the modulation of EC glazing was not coupled in a scenario with on/off light switching since such lighting control was intended to simulate manual control of artificial lights by the occupants. As discussed previously, while in this study the on/off switching was modelled as being perfectly daylight-linked, this cannot be guaranteed in real-life situations. In addition, coupling a glazing system that allows the gradual modulation of internal illuminance in the range of 10 - 80% with a lighting system that provides 'all or nothing' illuminance would negate the energy saving benefits expected from the advanced window system. As such, daylight-linked continuous dimming of electric lighting coupled with the modulation of the EC transmittance in a fully automated system was considered a more appropriate (and feasible) scenario that can potentially maximize energy savings.

However, the annual electric lighting energy demand was calculated per m^2 of floor area, and the electric energy production from the BIPVs was calculated per m^2 of facade area. Hence, it was necessary to first 'unify' the space reference in order to compare/relate the calculated values. Considering the physical dimensions of the office model, Figure 7-7, the

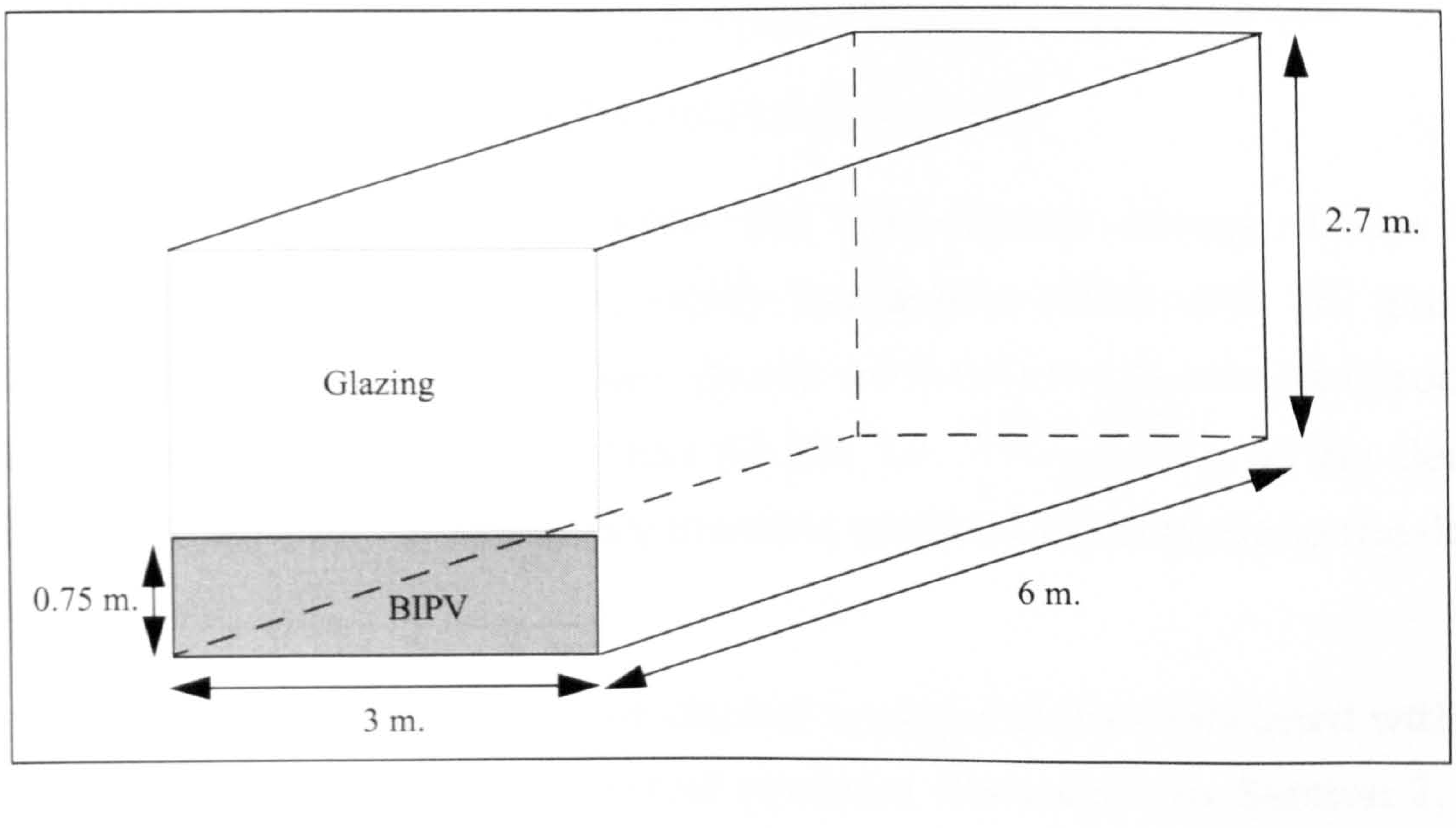

Figure 7-7 Office unit with BIPVs and continuous dimming control of electric lighting

predicted values of annual electric lighting energy demand (obtained as discussed in Section 7.1.2) were multiplied by the office floor area (18 m^2) to produce the total annual lighting energy demand for the whole office. Similarly, The annual BIPV energy production values were multiplied by the PV-covered facade area (2.25 m^2) to produce the office's total annual BIPV energy production. Then, in order to reference all the values to one unit (m.) of office facade width, the total annual lighting energy demand and the total annual BIPV energy production were both divided by the office facade width (3 m.). In other words,

$$\left(\frac{\text{Lighting Energy demand}}{m^2 \text{ floor area}}\right) \times \frac{18m^2}{3m} = \left(\frac{\text{Lighting Energy demand}}{m \text{ facade width}}\right)$$

$$\left(\frac{\text{BIPV energy production}}{m^2 \text{ facade area}}\right) \times \frac{2.25m^2}{3m} = \left(\frac{\text{BIPV energy production}}{m \text{ facade width}}\right)$$

For example, as shown in Figure 5-16 and Table 5-9, a south-facing UK office, with EC glazing of non-linear control and continuously-dimmed electric lighting, consumes 15.1 kWh/m^2 of office floor area. Therefore,

15.1 kWh/m^2 x $\frac{18m^2}{3m}$ = 90.6 kWh/m of facade width. It was also shown in Figure 6-9 and Table 6-3 that with the same southern orientation, BIPVs can produce 70.7 kWh/m^2 of the office facade area, and therefore,

70.7 kWh/m^2 x $\frac{2.25m^2}{3m}$ = 53 kWh/m of facade width.

It is now straightforward to relate the two electric energy values and conclude that for example, in a south-facing Kew office with EC glazing, whose transmittance control is non-linear, a PV-covered facade can produce enough electricity annually to offset 58.5%, i.e., $\left(\frac{53 \times 100\%}{90.6}\right)$, of the electric energy consumed by continuously dimmed artificial lighting along the depth of the office (6 m.).

This procedure was applied on all electric energy values associated with the different facade devices and control systems discussed in Section 7.1.2., and the results are shown in the next sections.

7.3.1 Manual Blinds, On/Off Light Switching, EC Glazing, and Continuous Light Dimming

After the total electric lighting energy consumed annually by an on/off light switching system associated with manual blinds operation on a window with clear, antisun green, and antisun bronze glazings was calculated, the energy values, which referred to unit area of office floor, were then adjusted to refer to unit width of office facade, as detailed above. As discussed in Section 4.3.1, for on/off light switching, the electric lighting at the three luminaires was set to full 'power on' at any working hour when 500 lux is not attained by daylight alone in each of the three office zones under the luminaires. Otherwise, the electric lighting was completely switched off.

Similarly, the values of total electric energy produced annually by BIPVs and referenced to unit area of the office facade were adjusted to refer to unit width of the office facade. The results are shown using bar charts in Figure 7-8 for all locations for the main four azimuth orientations. The electric lighting energy consumption of a system which involves continuous light dimming and EC glazing of linear and non-linear control are also included in the figure for comparison, although they are discussed in more detail in the next section.

From the figure, the following points can be noted:

- The lower the transmittance of the window glazing, the higher the electric lighting energy demand for all orientations and for all locations in both hemispheres, i.e., with clear double glazing, the lighting consumption is lowest and with antisun bronze, it is highest.
- While the differences are not substantial, in the northern hemisphere, a north-facing office will generally consume more electric energy for lighting than offices of other orientations. In locations close to the equator, the consumptions of the four azimuth orientations are very similar.

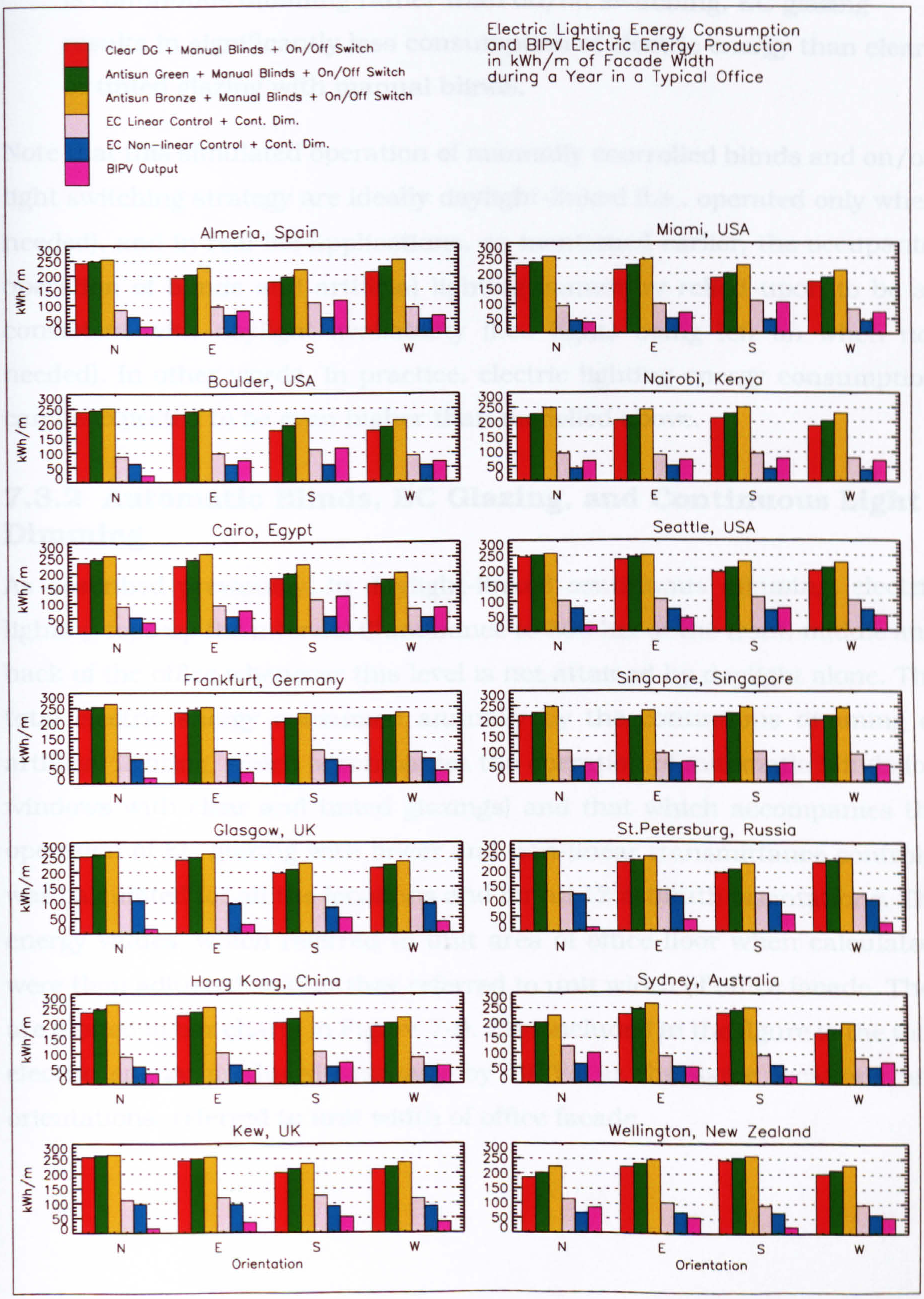

Figure 7-8 Annual electric lighting energy demand for on/off switching with manual blinds and for continuous dimming with EC glazing and the electric energy production of BIPVs in different locations around the world

- Notwithstanding the fact that the associated lighting control strategy is continuous dimming rather than on/off switching, EC glazing results in significantly less consumption of electric energy than clear or tinted glazing with manual blinds.

Note that this simulated operation of manually controlled blinds and on/off light switching strategy are ideally daylight-linked (i.e., operated only when needed), and in real life applications, as mentioned earlier, the occupants' operation of blinds and artificial lighting cannot by relied upon to be as consistent with daylight availability (i.e., lights being left on when not needed). In other words, in practice, electric lighting energy consumption can be expected to be even higher than modelled above.

7.3.2 Automatic Blinds, EC Glazing, and Continuous Light Dimming

As described previously, in daylight-linked continuous dimming, electric lighting tops up the internal illuminance to 500 lux at the front, middle and back of the office whenever this level is not attained by daylight alone. The total electric energy consumed annually by the continuous dimming of artificial lighting, which accompanies the operation of automatic blinds (on windows with clear and tinted glazings) and that which accompanies the operation of EC glazing with linear and non-linear transmittance controls, was calculated for all the locations and for all 12 azimuth orientations. The energy values, which referred to unit area of office floor when calculated, were then adjusted so that they referred to unit width of office facade. They are plotted in bar charts in Figure 7-9. Also included in the figure is the total electric energy produced annually by BIPVs at the same locations and orientations, referred to unit width of office facade.

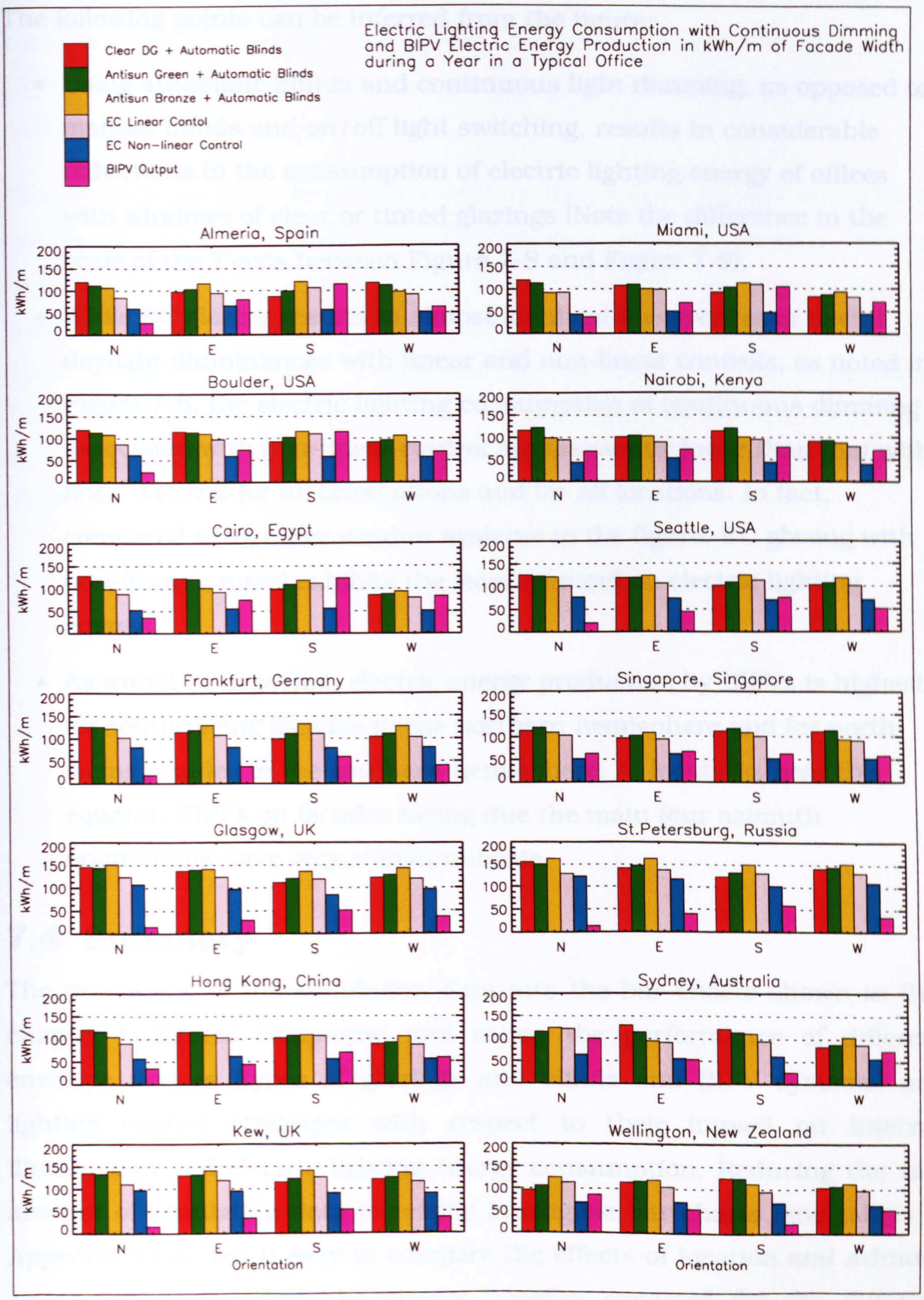

Figure 7-9 Annual electric lighting energy demand for continuous dimming with automatic blinds and with EC glazing and the electric energy production of BIPVs in different locations around the world

The following points can be inferred from the figure:

- Using automatic blinds and continuous light dimming, as opposed to manual blinds and on/off light switching, results in considerable reductions in the consumption of electric lighting energy of offices with windows of clear or tinted glazings (Note the difference in the scale of the Y-axis between Figure 7-8 and Figure 7-9).
- While EC glazing results in almost identical occurrences of useful daylight illuminances with linear and non-linear controls, as noted in Figure 7-6, the electric lighting consumption of continuous dimming associated with non-linear control is consistently lower than that with linear control for all orientations and for all locations. In fact, compared to all other window systems in the figure, EC glazing with non-linear control exhibits the least demand on electric lighting energy.
- As would be expected, electric energy production by BIPVs is highest for south-facing facades in the northern hemisphere and for north-facing facades in the southern hemisphere. At locations near the equator, BIPVs on facades facing due the main four azimuth orientations have very similar outputs.

7.4 Summary

The processing of the simulation data into the bar charts shown in this chapter facilitates comparing and rating the performance of different envelope devices (types of glazings and blinds and BIPV systems) and lighting control strategies with respect to their impact on internal illumination and electric lighting energy consumption. Reducing the vast amount of simulation data to readily intelligible bar charts (and tables in Appendix D) makes it easy to compare the effects of location and azimuth orientation and assess the energy benefits expected for the different scenarios. This information may be useful to architects, building designers, and developers in evaluating the validity of integrating such systems into their buildings. It may also be of use to material developers since it can assist them in their research on improving their products and optimizing performance.

Note that while the illumination and energy values shown above were calculated for an unshaded/unobstructed vertical facade, similar calculations for a building surface of any tilt and with any amount of shading can be performed by re-calculating the DCMs after adjusting the office model to incorporate a different tilt and/or surrounding structures. The incident irradiation and internal daylight illumination values can then be re-derived for any azimuth orientation and for any climate using the modified XDAPS automatic modelling and analysis tool.

Chapter

8

Discussion and Conclusions

"Do not go gentle into that good night,
Old age should burn and rave at close of day;
Rage, rage against the dying of the light."

DYLAN THOMAS 1914-1953 (*DO NOT GO GENTLE INTO THAT GOOD NIGHT*)

8.1 Summary

In this study, the aim has been to simulate/model and assess the performance of advanced envelope systems under realistic time-varying climatic conditions in order to accurately quantify their impact on the internal daylight illumination and consumption of electric lighting energy in office buildings. The work involved the adaptation of suitable calculation approaches and the development of investigative models and custom-written data analysis programs. The study was prompted by advances in daylight modelling techniques, which allow illuminance predictions that are more accurate and realistic than previously possible, the need to suggest some variations to orthodox design concepts, and the recent developments in building envelope technologies, particularly switchable/dynamic fenestration devices.

First, a review was carried out of the existing literature on daylight implementation strategies in buildings, artificial lighting components, and lighting controls in non-domestic buildings, and advanced envelope systems were introduced (Chapter 2). Then, different approaches for modelling daylight illuminance were reviewed, and the XDAPS *Radiance* implementation of the daylight coefficient approach was selected (and adapted) for modelling time-varying internal illuminances and external irradiation (Chapter 3). The implementation involved the calculation of three daylight coefficient matrices (DCMs) in order to derive four components of illuminance (and irradiance) representing direct and indirect illuminances (and irradiances) due to the sun and direct and indirect illuminances (and irradiances) due to the sky.

In Chapter 4, the methods by which predicted internal daylight illuminance values are typically utilised to assess the suitability of daylight for task functions were revised, some improvements were proposed to the assessment methods before a new daylight evaluation metric was introduced. The metric was based on the concept of classifying the internal illuminance values in the range of 100 - 2000 lux as useful daylight illuminances and computing the percentage of the working year during which the workplane illuminances in the core length of the office fall into that range. This metric was utilized as a tool for appraising the availability and usefulness of daylight in an office space rather than at a point, based on realistic time-varying daylight illuminances and for different azimuth orientations.

Different window devices were reviewed in Chapter 5, and their performance with respect to the internal daylight illumination was modelled and evaluated using the new metric, i.e., calculating the resulting occurrences of useful daylight illuminances during the working year. The impact on one aspect of visual comfort was also addressed. The technologies that were investigated for the transparent area of a building envelope included tinted glazings, manual blinds, automated blinds, and electrochromic glazing (with linear and non-linear modulations of transmittance). For the opaque area of the envelope, building-integrated photovoltaics were examined. Feasible/realistic scenarios coupling the operation of switchable window devices with different daylight-linked electric lighting controls (on/off switching and continuous dimming) were also modelled in order for the electric energy consumed by artificial lighting to be computed.

A review of PVs and their integration into building envelopes was carried out (Chapter 6). The performance of a building-integrated PV system was then simulated using a realistic model and actual meteorological data. First, the irradiation incident on the vertical PV facade was derived using calculated DCMs, and the PV cell temperature was calculated using a thermal model. Then, the electric output produced by the BIPV system was predicted for different azimuth orientations using the electrical characteristics of a widely-used high-efficiency PV module.

In Chapter 7, the validity of applying the adopted approaches and the developed models for assessing the performance of advanced envelope systems in different climatic zones was studied. The grouping of the performance results as functions of device properties and implementation strategies facilitated comparing and rating the different systems.

8.2 Conclusions

The results obtained in this study can be outlined as follows:

- Carefully designed (for example, suitable orientation and location) fenestration systems can be used to effectively modulate daylight admittance and, coupled with appropriate lighting control strategies, to reduce the use of electric lighting, while potentially meeting the occupants' lighting quality and quantity requirements in office interiors.

- New opportunities in daylight modelling have been created by techniques such as the daylight coefficient approach and the XDAPS formulation, which use realistic time-varying meteorological conditions to allow daylight illuminance predictions that are more accurate than previously possible with traditional modelling techniques.
- Commonly used methods for evaluating daylight illuminance values at each calculation point independently of the others, such as cumulative totals and frequency histograms, have room for improvement.
- The introduced useful daylight illuminances metric allows the simultaneous quantification of internal daylight illuminance at calculation points along the depth of a side-lit office, rather than analysing each point separately. The frequency of occurrences of useful daylight illuminances addresses the totality of a space and provides a quantity that describes the availability and suitability of daylight illuminance in a space rather than just at a point. Also, by definition, it provides an indication of the illumination uniformity in the space since the illuminances will need to be in the range of 100 - 2000 lux in order to be considered useful.
- In terms of simplicity, this metric is comparable with daylight factors, i.e., a single number that characterises illuminance performance and that can be easily understood by architects and designers. In contrast to DFs, however, it is based on realistic time-varying sky and sun conditions.

- The automatic modelling and analysis tool (presented in Chapter 7), which consists of grouped custom-written and adapted XDAPS programs and uses the useful daylight illuminances metric, is a powerful tool which can be utilized for realistically evaluating the performance of innovative window systems and their impact on the internal daylight illuminance under a wide range of climatic conditions and for all facade orientations. The impact of the associated lighting control strategies on the electric lighting energy consumption can also be evaluated.
- Compared to the other examined types of glazing and shading devices, and in all the considered climates, EC glazing (with linear or non-linear modulation of transmittance) results in the maximum fraction of the working year during which the office receives useful daylight illuminances. In addition, compared to all the investigated scenarios, EC glazing with non-linear modulation of transmittance coupled with daylight-linked continuous light dimming consistently exhibits the least demand on electric lighting energy for all azimuth orientations and for all climate locations.
- Dynamic facade systems, such as electrochromic glazing or automatic blinds, and their integration with daylight-linked continuously dimmed artificial lighting in an automatic system, can significantly improve the luminous environment inside office buildings and effectively reduce the demand for electric lighting, compared to static glazings, manual blinds, and manual on/off light switching.
- The XDAPS formulation (and the daylight coefficient approach) allows the prediction of hourly (or less) incident irradiation on vertical PV facades based on real time-varying meteorological conditions, and consequently, together with the evaluation of PV cell temperature, allows a realistic time-varying estimation of the BIPV generated electric power.

- Integrating PVs into the facades of office buildings is a viable option in a wide range of climatic conditions, and their electric output can potentially contribute to further reducing the demand for primary energy.

An important note is that the fundamental step before increasing the amount of energy generated, for example by integrating devices such as PVs into buildings, is to first maximise the building's energy efficiency, i.e., reduce the consumption of fossil fuels and utilize energy more efficiently and cost-effectively. Based on the results obtained in this study for the base case of a typical office with manual blinds and on/off light switching, there is clearly plenty of room for energy savings and improvements in internal daylight illumination. Switchable window devices, such as automatic blinds and EC glazing, were demonstrated to have the potential to efficiently control daylight admission in non-domestic buildings and provide useful daylight illuminances most of the working year.

In addition, coupled with daylight-linked lighting controls, these switchable devices were shown to have the potential to significantly reduce the need for artificial lighting. Reviewing all the energy results obtained in Chapter 7, it was found that an office (with the characteristics of the studied model) with daylight-linked automatic blinds coupled with continuous light dimming requires 47 - 62% (mean of 53%) of the electric lighting energy required by the base case (i.e., an office with manual blinds and on/off light switching), depending on location and orientation. Even more impressive were the results of an office with EC glazing with non-linear transmittance control coupled with daylight-linked continuous light dimming, which was found to require only 19 - 52% (mean of 32%) of the electric lighting energy consumed by the base case, depending on location and azimuth orientation.

Subsequent to the minimization of the energy demand in non-domestic buildings using the above systems, replacing part of the primary energy consumed with renewable energy (through energy production from PVs or other renewable energy sources) would be more appreciated. This is because with the standard levels of energy consumption, the results show that BIPVs can replace only 5 - 67% (mean of 28%) of the electric lighting energy demand of the base case office, depending on location and azimuth orientation. Hence, it is recommended that all the above innovative technologies deserve to be considered as viable options in future energy-efficiency strategies in non-domestic buildings.

It is hoped that this study may prove to be useful to architects, building designers, and developers, and that the proposed models and assessment methods can be helpful in ranking the performance of advanced envelope systems, evaluating the viability of integrating such systems into buildings, and facilitating the selection of systems that are most appropriate for particular designs, orientations, and climates.

8.3 Suggestions for Future Work

Potential future studies can possibly include tuning the mixing function of the sky blend in the XDAPS formulation to suit skies of different characteristics once the vertical illuminance data becomes available. It would then be possible to investigate if/how this affects the previously obtained results. Also worth investigating is the use of more complex models for the sky luminous efficacy (instead of a simple constant value), i.e., time-varying, and the use of short time-step weather data.

When more studies on occupants' preferences are produced, perhaps it would be possible to investigate if the range of useful daylight illuminances (i.e., 100 - 2000 lux) should be varied depending on the nature of the incident daylight, i.e., whether direct or diffuse. These studies can also assist in more accurately evaluating occupants' acceptance of dynamic envelope and lighting systems.

Future studies can potentially also involve modelling the impact that EC glazing and daylight-linked continuous light dimming can have on the cooling and air-conditioning loads in office buildings as well as artificial lighting, i.e., integrate daylight modelling, thermal modelling, and energy modelling, based on real time-varying meteorological data, in a holistic building system.

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Appendix

A Ancillary Equations

A.1 Error Analysis Equations

x = predicted and X = *measured*.

Relative Error (RER)

$$RER = \frac{x - X}{X} \times 100\% \tag{A-1}$$

Mean Bias Error (MBE)

$$MBE = \frac{\sum_{i=1}^{n}\left(\frac{x_i - X_i}{X_i}\right)}{n} \times 100\% \tag{A-2}$$

Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{x_i - X_i}{X_i}\right)^2}{n}} \times 100\% \tag{A-3}$$

Appendix B

PV Module Specifications

B.1 Physical Characteristics

The BP 585 is an 85-Watt high-efficiency monocrystalline photovoltaic module. It consists of premium laser-grooved buried-grid monocrystalline cells, which minimizes cell front shading and maximizes efficiency. Cells (36 connected in series) are laminated between sheets of ethylene vinyl acetate (EVA) and high transmissivity low-iron 3 mm. tempered glass. The unframed laminate version of the BP 585, used in the models of this study, is 1197 mm. high, 530 mm. wide, and 18 mm. thick [BP Solar, 2002].

B.2 Electrical Characteristics

At Standard Test Conditions (STC)

Irradiance, G_{STC} = 1000 W/m^2

Module Temperature, T_{STC} = 25°C

Short circuit current, I_{sc} = 5.0 A

Open circuit voltage, V_{oc} = 22.1 V

Current at maximum power, I_{max} = 4.72 A

Voltage at maximum power, V_{max} = 18.0 V

Maximum power, P_{max} = 85 W

Temperature coefficient of short circuit current, $\mu_{I_{sc}} = (0.065 \pm 0.015)\%/°C$

Temperature coefficient of open circuit voltage, $\mu_{V_{oc}} = -(80 \pm 10)$ mV/°C

Temperature coefficient of power, $\mu_P = -(0.5 \pm 0.05)\%/°C$

At Nominal Operating Cell Temperature (NOCT) Conditions

Irradiance, G_{NOCT} = 800 W/m^2

Ambient Temperature, $T_{a, NOCT}$ = 20°C

Module Temperature, $T_{c, NOCT}$ = 47±2°C

Appendix

C Ancillary PV Reviews

C.1 Thermal Models for Calculating PV Cell Temperature

In this study, the thermal model presented by Duffie et al. [Duffie et al., 1991] was adopted for calculating the PV module temperature in the modelled system (Chapter 6). Three more simple thermal models were also reviewed during the course of this study (described below). However, since they were experimental models, there was concern that the constants used in the equations might be material and construction dependent.

C.1.1 The King et al. Model

A simple model was presented in [King et al., 1998] to provide reasonably accurate estimates (5C) of module back surface temperature for typical flat-plate modules, near thermal equilibrium, mounted in an open rack structure. The relationship is given by the following equation:

$$T_m = \frac{G_T}{G_{STC}}[T_1 \cdot e^{b \cdot WS} + T_2] + T_a \qquad \text{(C-1)}$$

where

T_m = Back surface module temperature (°C).

T_a = Ambient temperature (°C).

G_T = Irradiance incident on the module (W/m^2).

G_{STC} = Reference irradiance, i.e., 1000 W/m^2 at STC.

WS = Wind speed measured at standard 10-m. height (m/s).

T_1 = Empirical coefficient determining the upper temperature limit at low wind speeds.

T_2 = Empirical coefficient determining the lower temperature limit at high wind speeds.

b = Empirical coefficient determining the rate that module temperature drops as wind speed increases.

The cell temperature inside the module is typically warmer than the back surface, and the temperature difference between the cell and the back surface, ΔT, depends on the intensity of the solar irradiance and the type and thickness of the materials used for the substrate of the module. The relationship between the module back surface temperature and the cell temperature is given by the following equation:

$$T_c = T_m + \left(\frac{G_T}{G_{STC}} \times \Delta T\right) \tag{C-2}$$

where

T_c = Module temperature (°C).

Table C-1 gives the parameters found to give good agreement with

Module type	T_1 (°C)	T_2 (°C)	b	DT
Glass/Cell/Glass	25.0	8.2	-0.112	2
Glass/Cell/Tedlar	19.6	11.6	-0.223	3

Table C-1 Empirical coefficients for module/cell temperature estimation, for two typical module designs [King et al., 1998]

measured temperatures for the following two different module types: cells encapsulated between two sheets of glass, and cells encapsulated between a front glass cover and an opaque backing sheet. PV modules integrated into buildings, however, will have much less convective cooling from the rear surface. For example, roof-integrated modules may operate at temperatures 10°C to 20°C above those in open racks [King et al., 1998].

C.1.2 The Lasnier et al. Model

In [Lasnier et al., 1990], the following experimental model was given to predict module temperature from irradiance, ambient temperature, and wind speed:

$$T_c = T_a + \theta_{G_T}(1 + \theta_{T_a} T_a)(1 - \theta_{v_w} v_w) G_T \tag{C-3}$$

where

T_c = Module temperature (°C).

T_a = Ambient temperature (°C).

v_w = Wind speed (m/s), taken to be constant and equal to 1 m/s.

G_T = Irradiance incident on the module (W/m^2).

$\theta_{G_T} = 0.0138$, a constant determined by experimental data.

$\theta_{T_a} = 0.031$, a constant determined by experimental data.

$\theta_{v_w} = 0.042$, a constant determined by experimental data.

Therefore, Eq C-3 can be re-written as

$$T_c = T_a + 0.0138(1 + 0.031 T_a)(1 - 0.042) G_T \tag{C-4}$$

C.1.3 The Lorenzo et al. & Wilshaw et al. Model

The temperature model in [Lorenzo et al., 1994] depends exclusively on the irradiance and the ambient temperature according to the following linear equation:

$$T_c = T_a + CG_T \tag{C-5}$$

where

T_c = Module temperature (°C).

T_a = Ambient temperature (°C).

G_T = Irradiance incident on the module (W/m^2).

C is a constant with the value of

$$C = \frac{(T_{c,NOCT} - T_{a,NOCT})}{G_{T,NOCT}} \tag{C-6}$$

where

$T_{c,NOCT}$ = Nominal operating cell temperature (NOCT) in °C.

$T_{a,NOCT}$ = Ambient temperature of 20°C (at NOCT).

$G_{T,NOCT}$ = 800 W/m^2 (at NOCT).

This relation assumes that the heat dissipation from the cells to the environment is dominated by conduction through the encapsulation, rather than convection from the surface, and the effect of the wind velocity is disregarded.

The value of $T_{c,NOCT}$ varies from approximately 42°C to 46°C, giving a value of C equal to ~0.0275 - 0.0325 °C/(W/m^2). If $T_{c,NOCT}$ is unknown, a reasonable approximation is $C = 0.03$ °C/(W/m^2) [Lorenzo et al., 1994].

Wilshaw et al. [Wilshaw et al., 1996] obtained the following simultaneous experimental results under UK climatic conditions:

- $C = 0.023$ °C/(W/m^2) for a free standing PV system (free flow of air around it).

- $C = 0.035\,°C/(W/m^2)$ for both a PV rainscreen overcladding system and a PV curtain wall facade system where the back of the PVs was naturally ventilated using the stack effect in the air gap between the modules and the building.
- $C = 0.04\,°C/(W/m^2)$ for a vertical rainscreen overcladding system, where rock wool insulation was *used to completely* fill the space between the modules and the building.

As might be expected, the free standing system had the smallest temperature coefficient which resulted in the lowest module temperatures for any given irradiance and ambient temperature. The above reported results, however, show an increase of approximately 50% in the temperature coefficient for the rainscreen overcladding and curtain wall systems, where the air flow was restricted. For the insulated rainscreen overcladding system, where very little air flow was possible, the increase in the temperature coefficient was approximately 75% compared to the free standing system [Wilshaw et al., 1996].

Appendix D

Tabulated Results

D.1 Useful Daylight Illuminances

Location	Glazing	Percentages of the Working Year			
		N	E	S	W
Almeria, Spain	Clear	40.6%	29.4%	13.3%	11.4%
	Green	53.6%	34.8%	15.2%	24.1%
	Bronze	73.0%	40.6%	21.1%	52.7%
Boulder, USA	Clear	43.6%	27.3%	7.0%	23.7%
	Green	55.5%	37.9%	10.7%	28.4%
	Bronze	74.1%	57.1%	20.5%	38.7%
Cairo, Egypt	Clear	27.3%	15.7%	6.1%	20.3%
	Green	42.1%	29.3%	9.8%	27.1%
	Bronze	69.6%	59.8%	20.0%	37.6%
Frankfurt, Germany	Clear	40.6%	36.7%	29.1%	35.3%
	Green	49.1%	44.3%	32.3%	40.7%
	Bronze	65.5%	52.4%	32.9%	44.0%
Glasgow, UK	Clear	37.8%	30.0%	22.5%	31.4%
	Green	45.6%	35.6%	25.0%	34.6%
	Bronze	55.3%	50.6%	29.2%	38.0%
Hong Kong, China	Clear	30.6%	23.7%	16.2%	25.6%
	Green	41.0%	31.4%	21.0%	31.6%
	Bronze	67.3%	52.6%	36.9%	40.4%

Table D-1 Useful daylight illuminances with unshaded clear and tinted glazings

Kew, UK	Clear	43.6%	36.3%	17.6%	24.6%
	Green	51.4%	42.7%	20.2%	29.3%
	Bronze	63.1%	51.6%	25.6%	37.7%
Miami, USA	Clear	23.0%	17.5%	6.3%	17.5%
	Green	34.9%	25.7%	10.4%	23.5%
	Bronze	63.4%	48.8%	20.7%	36.9%
Nairobi, Kenya	Clear	16.6%	26.0%	16.3%	16.4%
	Green	23.7%	31.3%	23.0%	24.4%
	Bronze	46.9%	46.7%	46.8%	45.1%
Seattle, USA	Clear	41.3%	33.0%	16.6%	26.9%
	Green	50.2%	40.9%	20.9%	31.6%
	Bronze	64.3%	54.3%	29.6%	40.2%
Singapore, Singapore	Clear	22.0%	25.1%	22.1%	14.3%
	Green	26.3%	32.3%	27.0%	19.3%
	Bronze	43.8%	43.8%	44.1%	47.2%
St.Petersburg, Russia	Clear	42.6%	33.7%	18.6%	28.3%
	Green	48.9%	36.3%	19.7%	32.6%
	Bronze	55.7%	37.1%	23.0%	41.2%
Sydney, Australia	Clear	3.6%	14.1%	35.8%	26.2%
	Green	6.2%	30.4%	46.1%	30.3%
	Bronze	16.1%	66.2%	66.3%	35.4%
Wellington, New Zealand	Clear	14.5%	28.3%	38.3%	24.4%
	Green	16.7%	36.0%	48.8%	30.0%
	Bronze	23.0%	49.3%	69.2%	42.3%

Table D-1 Useful daylight illuminances with unshaded clear and tinted glazings

Location	Glazing	Percentages of the Working Year			
		N	E	S	W
Almeria, Spain	Clear	52.3%	53.0%	58.8%	60.3%
	Green	43.0%	50.9%	58.8%	43.7%
	Bronze	39.0%	45.2%	52.0%	29.8%
Boulder, USA	Clear	53.2%	51.5%	56.8%	56.7%
	Green	45.6%	43.6%	54.6%	55.5%
	Bronze	42.1%	40.7%	46.5%	52.8%
Cairo, Egypt	Clear	61.2%	58.7%	64.7%	52.5%
	Green	45.3%	39.6%	62.4%	49.2%
	Bronze	33.0%	25.6%	43.6%	48.7%
Frankfurt, Germany	Clear	42.5%	40.8%	45.7%	37.6%
	Green	34.0%	36.7%	46.6%	37.3%
	Bronze	24.5%	31.1%	43.6%	36.7%
Glasgow, UK	Clear	37.3%	43.1%	53.7%	41.9%
	Green	30.4%	35.8%	52.7%	39.6%
	Bronze	25.8%	28.0%	47.1%	36.9%
Hong Kong, China	Clear	55.8%	55.5%	62.1%	50.0%
	Green	38.9%	44.6%	52.8%	49.0%
	Bronze	28.4%	30.2%	36.7%	46.3%
Kew, UK	Clear	35.3%	39.2%	47.7%	43.1%
	Green	28.2%	35.1%	46.7%	39.7%
	Bronze	29.3%	32.3%	43.0%	35.9%

Table D-2 Useful daylight illuminances with manual blinds and clear and tinted glazings

Miami, USA	Clear	66.8%	61.9%	69.6%	56.0%
	Green	51.6%	51.6%	65.8%	53.0%
	Bronze	30.3%	36.1%	47.7%	49.5%
Nairobi, Kenya	Clear	79.0%	56.8%	77.7%	61.2%
	Green	64.5%	45.0%	63.1%	51.7%
	Bronze	36.7%	37.5%	37.3%	39.9%
Seattle, USA	Clear	45.5%	46.5%	52.9%	47.1%
	Green	37.9%	39.1%	50.4%	44.2%
	Bronze	32.7%	36.3%	46.0%	40.3%
Singapore, Singapore	Clear	72.1%	47.4%	71.8%	65.4%
	Green	62.6%	42.8%	61.1%	53.7%
	Bronze	36.9%	37.4%	37.8%	28.7%
St.Petersburg, Russia	Clear	31.1%	40.5%	44.0%	39.4%
	Green	25.5%	38.4%	42.6%	33.9%
	Bronze	28.9%	33.6%	40.5%	32.4%
Sydney, Australia	Clear	63.8%	54.7%	57.9%	49.4%
	Green	61.0%	33.2%	47.0%	49.6%
	Bronze	44.5%	23.3%	41.3%	49.0%
Wellington, New Zealand	Clear	55.3%	49.4%	47.0%	50.7%
	Green	52.9%	43.3%	36.8%	46.6%
	Bronze	48.7%	37.3%	30.6%	42.4%

Table D-2 Useful daylight illuminances with manual blinds and clear and tinted glazings

Location	Glazing	Percentages of the Working Year			
		N	E	S	W
Almeria, Spain	Clear	74.9%	65.5%	66.7%	68.4%
	Green	74.1%	65.0%	67.3%	63.6%
	Bronze	75.9%	63.1%	63.4%	72.4%
Boulder, USA	Clear	77.2%	73.6%	62.5%	65.8%
	Green	75.3%	71.2%	62.9%	66.7%
	Bronze	77.3%	72.3%	60.4%	68.4%
Cairo, Egypt	Clear	77.2%	72.4%	69.4%	60.9%
	Green	72.4%	65.1%	70.2%	61.9%
	Bronze	76.0%	75.0%	58.3%	66.5%
Frankfurt, Germany	Clear	70.1%	67.1%	65.3%	61.6%
	Green	66.2%	67.5%	67.1%	63.5%
	Bronze	66.6%	63.6%	61.9%	60.7%
Glasgow, UK	Clear	60.2%	63.3%	63.7%	59.4%
	Green	58.0%	58.9%	63.8%	58.3%
	Bronze	58.4%	60.6%	59.9%	55.0%
Hong Kong, China	Clear	77.0%	72.4%	74.0%	66.5%
	Green	67.5%	67.4%	68.7%	67.7%
	Bronze	75.6%	68.9%	64.6%	67.8%
Kew, UK	Clear	65.3%	64.8%	58.8%	58.6%
	Green	61.5%	62.9%	59.2%	58.0%
	Bronze	64.0%	61.1%	58.2%	57.5%

Table D-3 Useful daylight illuminances with automated blinds and clear and tinted glazings

Miami, USA	Clear	82.7%	76.7%	74.7%	66.7%
	Green	76.1%	72.0%	74.4%	67.4%
	Bronze	74.5%	71.4%	63.7%	70.8%
Nairobi, Kenya	Clear	88.1%	72.5%	87.4%	71.5%
	Green	78.2%	65.2%	78.0%	67.7%
	Bronze	72.2%	66.5%	73.9%	70.2%
Seattle, USA	Clear	72.1%	71.2%	64.2%	62.8%
	Green	69.7%	68.5%	64.6%	62.3%
	Bronze	67.2%	67.1%	64.0%	61.2%
Singapore, Singapore	Clear	85.0%	63.8%	84.4%	73.8%
	Green	77.9%	63.1%	77.2%	65.3%
	Bronze	67.3%	62.2%	68.5%	66.1%
St.Petersburg, Russia	Clear	55.5%	57.5%	52.6%	55.6%
	Green	52.1%	55.8%	51.0%	53.2%
	Bronze	55.7%	49.2%	50.2%	53.8%
Sydney, Australia	Clear	67.0%	66.1%	77.2%	61.8%
	Green	66.3%	59.6%	73.7%	63.4%
	Bronze	56.8%	75.5%	77.0%	63.1%
Wellington, New Zealand	Clear	64.8%	70.0%	74.0%	65.7%
	Green	64.0%	68.4%	69.0%	65.2%
	Bronze	62.7%	66.3%	70.6%	66.0%

Table D-3 Useful daylight illuminances with automated blinds and clear and tinted glazings

Location	Percentages of the Working Year							
	Linear Control				Non-linear Control			
	N	E	S	W	N	E	S	W
Almeria, Spain	87.8%	73.3%	72.1%	79.3%	88.1%	73.0%	70.1%	77.8%
Boulder, USA	87.2%	81.6%	66.9%	73.2%	88.6%	82.4%	66.9%	72.7%
Cairo, Egypt	87.5%	82.5%	72.1%	69.0%	88.2%	80.5%	73.3%	67.2%
Frankfurt, Germany	83.2%	79.7%	76.0%	74.8%	84.4%	81.3%	75.2%	75.2%
Glasgow, UK	74.0%	73.4%	70.1%	67.5%	72.7%	74.7%	70.6%	67.7%
Hong Kong, China	88.3%	81.0%	77.5%	75.6%	87.0%	84.6%	82.2%	77.4%
Kew, UK	78.1%	74.2%	67.4%	68.3%	77.4%	76.3%	68.0%	68.1%
Miami, USA	87.4%	81.3%	76.5%	76.5%	91.6%	83.5%	78.2%	75.5%
Nairobi, Kenya	89.4%	78.5%	88.7%	78.2%	91.2%	80.0%	91.3%	79.4%
Seattle, USA	81.8%	80.5%	72.5%	71.2%	83.9%	82.1%	73.0%	72.3%
Singapore, Singapore	84.8%	71.2%	85.8%	78.9%	90.4%	74.7%	90.1%	82.3%
St.Petersburg, Russia	68.9%	63.7%	58.3%	64.8%	67.8%	64.2%	57.3%	65.2%
Sydney, Australia	68.5%	82.2%	87.8%	70.6%	70.1%	82.1%	88.4%	71.0%
Wellington, New Zealand	70.6%	77.3%	83.1%	75.1%	70.8%	79.0%	84.8%	75.2%

Table D-4 Useful daylight illuminances with EC glazing of linear and non-linear control

D.2 Electric Lighting Energy Consumption

Location	Glazing	kWh/m of Facade Width			
		N	E	S	W
Almeria, Spain	Clear	241.3	192.2	177.6	209.1
	Green	247.4	203.5	193.5	227.6
	Bronze	253.8	226.0	218.1	250.1
Boulder, USA	Clear	238.9	230.0	176.1	175.5
	Green	243.7	240.4	192.6	187.1
	Bronze	250.8	244.6	217.1	209.5
Cairo, Egypt	Clear	234.2	223.6	182.7	163.3
	Green	244.4	244.0	197.9	176.7
	Bronze	256.8	263.2	227.9	199.4
Frankfurt, Germany	Clear	245.6	234.7	205.0	214.7
	Green	253.0	244.3	216.5	223.3
	Bronze	263.4	252.8	232.2	233.5
Glasgow, UK	Clear	251.9	240.3	196.7	214.5
	Green	258.6	249.3	209.0	223.4
	Bronze	268.0	261.2	229.4	235.6
Hong Kong, China	Clear	235.9	226.4	202.4	188.4
	Green	247.0	238.2	215.8	200.7
	Bronze	263.2	254.1	240.6	219.6
Kew, UK	Clear	254.9	242.9	202.7	212.9
	Green	260.3	249.5	215.6	222.5
	Bronze	263.3	255.8	233.7	237.4

Table D-5 Electric lighting consumption for on/off switching with manual blinds and clear and tinted glazings in kWh per m. of facade width

Miami, USA	Clear	227.2	211.9	184.7	172.6
	Green	238.1	227.5	199.4	186.4
	Bronze	256.2	245.6	226.7	209.3
Nairobi, Kenya	Clear	214.0	206.0	212.2	186.7
	Green	227.3	221.1	227.6	203.7
	Bronze	248.7	241.8	249.1	229.2
Seattle, USA	Clear	245.7	236.7	195.1	197.9
	Green	251.2	245.4	209.3	208.5
	Bronze	256.3	250.6	229.2	225.2
Singapore, Singapore	Clear	216.8	203.6	214.6	203.7
	Green	226.4	215.0	226.0	218.4
	Bronze	247.0	234.5	246.6	246.1
St.Petersburg, Russia	Clear	259.6	231.4	197.5	233.2
	Green	262.5	238.6	209.8	242.6
	Bronze	266.3	251.1	229.3	250.3
Sydney, Australia	Clear	186.3	229.4	233.4	168.8
	Green	201.6	247.1	243.2	180.9
	Bronze	225.4	264.2	252.1	202.0
Wellington, New Zealand	Clear	186.6	224.3	245.3	200.4
	Green	202.7	235.3	253.7	211.8
	Bronze	224.0	247.9	259.5	228.9

Table D-5 Electric lighting consumption for on/off switching with manual blinds and clear and tinted glazings in kWh per m. of facade width

Location	Glazing	kWh/m of Facade Width			
		N	E	S	W
Almeria, Spain	Clear	119.6	97.4	86.1	117.0
	Green	111.8	103.1	98.7	111.6
	Bronze	107.0	116.2	120.1	96.8
Boulder, USA	Clear	119.4	114.9	91.8	91.0
	Green	113.0	113.2	101.9	95.7
	Bronze	108.3	110.2	115.8	106.2
Cairo, Egypt	Clear	128.8	122.5	98.9	85.4
	Green	118.0	120.9	109.5	87.6
	Bronze	99.0	101.6	118.9	93.7
Frankfurt, Germany	Clear	125.7	114.1	99.4	103.6
	Green	125.7	118.2	111.2	110.7
	Bronze	122.0	129.8	133.2	127.4
Glasgow, UK	Clear	145.5	137.3	111.2	121.6
	Green	143.6	139.5	120.1	127.7
	Bronze	151.2	141.1	136.1	142.2
Hong Kong, China	Clear	120.6	115.3	102.4	88.4
	Green	116.3	115.9	107.3	91.8
	Bronze	104.5	109.2	108.8	105.3
Kew, UK	Clear	135.3	129.9	115.4	120.4
	Green	133.2	131.8	122.9	125.1
	Bronze	139.7	140.7	140.5	134.9

Table D-6 Electric lighting consumption for continuous dimming with automated blinds and clear and tinted glazings in kWh per m. of facade width

Miami, USA	Clear	119.7	107.0	92.6	82.3
	Green	113.2	109.7	103.6	86.8
	Bronze	91.9	99.7	113.2	93.1
Nairobi, Kenya	Clear	115.6	100.7	114.1	91.1
	Green	121.9	103.9	120.4	93.0
	Bronze	98.6	102.7	100.4	87.5
Seattle, USA	Clear	125.5	118.9	101.5	102.4
	Green	123.0	119.1	108.7	106.8
	Bronze	121.6	123.7	123.9	117.5
Singapore, Singapore	Clear	113.3	95.7	111.6	111.0
	Green	120.0	101.5	117.5	113.0
	Bronze	109.3	107.7	108.7	92.9
St.Petersburg, Russia	Clear	154.9	141.4	122.9	141.6
	Green	149.9	147.3	132.0	145.1
	Bronze	162.7	162.8	150.3	152.9
Sydney, Australia	Clear	101.2	129.9	121.0	83.4
	Green	114.2	114.3	114.1	88.6
	Bronze	123.5	95.0	111.9	104.1
Wellington, New Zealand	Clear	96.1	114.3	124.7	103.4
	Green	106.0	117.0	123.8	106.1
	Bronze	125.2	119.9	112.5	112.6

Table D-6 Electric lighting consumption for continuous dimming with automated blinds and clear and tinted glazings in kWh per m. of facade width

Location	kWh/m of Facade Width							
	Linear Control				Non-linear Control			
	N	E	S	W	N	E	S	W
Almeria, Spain	83.9	94.3	106.7	90.8	59.4	65.6	56.5	51.1
Boulder, USA	86.7	97.3	110.4	90.5	62.0	59.6	58.6	57.6
Cairo, Egypt	88.6	92.4	112.2	79.8	52.7	55.6	56.1	51.0
Frankfurt, Germany	102.3	108.0	111.4	103.1	81.2	81.3	79.8	80.7
Glasgow, UK	123.9	124.0	119.2	119.3	107.8	97.0	84.5	96.7
Hong Kong, China	90.0	103.0	106.9	86.9	57.3	62.0	55.5	55.4
Kew, UK	110.9	118.9	126.5	116.5	97.4	94.9	90.4	89.7
Miami, USA	92.8	98.7	109.5	81.9	43.7	50.3	47.7	44.4
Nairobi, Kenya	94.5	89.2	95.3	79.8	43.7	53.6	43.7	40.0
Seattle, USA	101.7	106.7	112.9	101.0	77.1	73.7	69.9	70.5
Singapore, Singapore	102.7	93.6	100.5	91.2	51.3	61.7	51.6	51.4
St.Petersburg, Russia	128.5	137.7	131.0	132.0	122.8	117.5	103.0	110.2
Sydney, Australia	121.3	91.7	95.4	87.7	63.8	55.7	62.0	57.4
Wellington, New Zealand	113.7	104.9	94.5	97.4	67.9	71.0	69.9	64.2

Table D-7 Electric lighting consumption for continuous dimming with EC glazing of linear and non-linear control in kWh per m. of facade width

D.3 BIPV Electric Energy Production

Location	kWh/m of facade width			
	N	E	S	W
Almeria, Spain	26.8	79.8	114.8	62.6
Boulder, USA	23.1	73.4	115.1	69.8
Cairo, Egypt	35.3	75.0	123.2	83.4
Frankfurt, Germany	18.5	38.0	59.8	40.1
Glasgow, UK	14.9	29.7	50.9	36.2
Hong Kong, China	35.3	43.9	69.7	58.5
Kew, UK	15.5	34.1	53.0	35.9
Miami, USA	37.6	69.1	104.6	71.5
Nairobi, Kenya	68.9	72.6	77.7	71.4
Seattle, USA	19.8	44.4	75.3	51.1
Singapore, Singapore	62.7	66.4	62.1	58.1
St.Petersburg, Russia	13.4	39.6	59.3	34.2
Sydney, Australia	99.6	53.5	25.7	73.9
Wellington, New Zealand	86.0	55.1	22.0	53.4

Table D-8 BIPV electric energy production in kWh per m. of facade width